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A Low-Signal-to-Noise-Ratio Sensor Framework Incorporating Improved Nighttime Capabilities in DIRSIG

Anthony P. Rizzuto

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A Low-Signal-to-Noise-Ratio Sensor Framework Incorporating Improved Nighttime Capabilities in DIRSIG

by

Anthony P. Rizzuto

B.S. Computer Engineering, The Pennsylvania State University, 2004

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Chester F. Carlson Center for Imaging Science Rochester Institute of Technology

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M.S. DEGREE THESIS

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A Low-Signal-to-Noise-Ratio Sensor Framework Incorporating Improved Nighttime Capabilities in DIRSIG

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Anthony P. Rizzuto

Submitted to the Chester F. Carlson Center for Imaging Science in partial fulfillment of the requirements for the Master of Science Degree at the Rochester Institute of Technology

Abstract

When designing new remote sensing systems, it is difficult to make apples-to-apples comparisons between designs because of the number of sensor parameters that can affect the final image. Using synthetic imagery and a computer sensor model allows for comparisons to be made between widely different sensor designs or between competing design parameters. Little work has been done in fully modeling low-SNR systems end-to-end for these types of comparisons. Currently DIRSIG has limited capability to accurately model nighttime scenes under new moon conditions or near large cities. An improved DIRSIG scene modeling capability is presented that incorporates all significant sources of nighttime radiance, including new models for urban glow and airglow, both taken from the astronomy community. A low-SNR sensor modeling tool is also presented that accounts for sensor components and noise sources to generate synthetic imagery from a DIRSIG scene. The various sensor parameters that affect SNR are discussed, and example imagery is shown with the new sensor modeling tool. New low-SNR detectors have recently been designed and marketed for remote sensing applications. A comparison of system parameters for a state-of-the-art low-SNR sensor is discussed, and a sample design trade study is presented for a hypothetical scene and sensor.
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Dedication

This is dedicated to the people who have motivated me to actually get something done instead of sitting on the couch and watching ESPN all day.
DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government.
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Chapter 1

Introduction

One of the biggest obstacles to persistent surveillance and situational awareness is that most passive remote sensing systems are designed for use in the reflective region of the Electromagnetic (EM) spectrum under bright daytime conditions where the light from the sun and sky can clearly illuminate a target on the ground. This limits their usefulness to only daytime and twilight hours. When the sun is below the horizon, systems that sense in the thermal region of the EM spectrum can be used to image the ground. Because of the materials needed to sense at those wavelengths, thermal imagers are currently more expensive and often have poorer spatial resolution than reflective systems. Additionally, these imagers often need to be cooled to reduce the self-emission of Infrared (IR) photons by the sensor itself.

The problem with using traditional daytime reflective systems to image a nighttime remote sensing scene is that there are few photons available at wavelengths in the reflective region, and the noise of these systems can be too high to produce useful images. The use of low Signal-to-Noise Ratio (SNR) reflective imagers offers an attractive alternative to thermal imagers because they have high spatial resolution and the potential for lower cost. Additionally, traditional reflective sensors made of silicon can operate without the need for cooling the optics or cooling the detector to cryogenic temperatures. Although cooling silicon detectors can significantly reduce detector noise,
this can be done with thermoelectric coolers that do not require a coolant, have no moving parts, and do not need a large cold enclosure.

New sensor designs have been created to allow reflective systems, generally made with silicon detectors, to image at night. There are two approaches to enhancing these daytime systems. The first is to reduce the noise in the system and collect as many photons as possible. Some of these system designs include back-illuminated Charge-Coupled Devices (CCDs) \cite{7,21,41} and hybrid sensors combining CCD and Complementary Metal-Oxide-Silicon (CMOS) technology \cite{3,6,32,33}. These systems may also have the potential to image in both daytime and nighttime scenes since they are essentially very sensitive versions of traditional systems. The second type of systems are designed to amplify the input signal, but generally also amplify the system noise. Examples of such systems include Image-Intensified CCDs (IICCDs) \cite{25,47} and avalanche photodiodes \cite{33,42,47}. Each design is very different, and each offers different advantages and disadvantages. There are other systems that are designed to count individual photons in extremely photon-starved environments, but these are generally not applicable for imaging. Aside from IICCDs, which have been in use since the mid 20th century, many of these system concepts are relatively new and still in development. Since these technologies have not had a chance to mature and there can be significant differences between system designs, it can be difficult to make fair scientific comparisons between them. It is nearly impossible to make an apples-to-apples comparison between different sensor designs because of this large variation in designs, materials, and manufacturing techniques. It is also difficult to determine which sensor parameters are best for a given scenario once a single overall design is specified.

The use of Synthetic Image Generation (SIG) tools offers a solution. Sensor systems can be fully modeled and tested on generated imagery without building and testing actual physical systems, making it an excellent tool for sensor trade studies. The Chester F. Carlson Center for Imaging Science (CIS) at Rochester Institute of Technology (RIT) created a radiometrically-accurate SIG tool that models sensor-reaching radiance and system specifications from first-principles for a given scene geometry, specified sources, and basic sensor parameters. The Digital Image and Remote Sensing Image Generation tool (DIRSIG) allows for sensors to be modeled and compared using
1.1. PROJECT GOALS

This research will accomplish the following goals:

1. Improve the sources of radiance that are used in DIRSIG for nighttime scene simulation.

2. Use DIRSIG to incorporate a sensor model for low-SNR sensors by adding components that are important in low-SNR scenes, particularly spectral responsivity and noise characteristics.

3. Conduct a proof-of-concept trade study on the effectiveness of different sensor design parameters to produce useful imagery in a low-SNR scene, demonstrating the capability of the modeling environment.
Chapter 2

Background

2.1 The Image Chain

It is often convenient to discuss an imaging system as an “imaging chain,” where each “link” in the chain is a process that transfers energy or information from one form to another in a discrete step. This is a very useful approach, particularly in system modeling, because it allows individual parts of the system to be studied independently. For example, a scene with specified geometry and specified sources will produce a particular radiance at the sensor. We can separate the optics and detector from the sources of radiance if we simply want to study the effects of different sources in the scene. If we want instead to study various optical systems and how they affect the output imagery, we can replace the optics “link” in the chain with a different design or different specifications. It allows for a quantitative analysis of the system and allows for confidence levels to be placed on the different components of the system. While each event in the chain can influence the others, they can be thought of as discrete steps, allowing strong and weak links in the chain to be identified.

The major parts of the imaging chain for the purpose of this work include:

1. Sources of EM flux – where the light originates

2. Scene radiometry – light interacting with the scene
3. Sensor optics – collecting and focusing the light on the detector

4. Photosensitive detector – how the light is sensed and converted to a measurable quantity

5. Image-processing algorithms – manipulations to improve or exploit the imagery

6. Display to the user

Each link in the chain can often in turn be broken up into smaller and smaller links. This work will focus on items 1–4 listed above, which will be discussed in more detail in subsequent sections.

2.1.1 Sources

In passive remote sensing, we are concerned with multiple sources of energy that react with the environment and reach the sensor. For remote sensing in the visible and reflective IR regions of the EM spectrum, these can be very warm objects (e.g., the sun, open flames, incandescent light bulbs) or physical molecular processes that emit photons (e.g., fluorescent light bulbs). During the day, the dominant source of scene radiance is the sun. Some photons from the sun shine directly on the target, and other photons are scattered by the atmosphere or reflected off of objects in the scene and illuminate the target. Because the sun emits so much energy, other sources are negligible.

Since the overall radiance in the reflective region is considerably lower in a nighttime scene, there are other sources that become significant. Many of these sources are present during the day, but the sun and solar scattering are orders of magnitude more intense. The light reflected off the moon interacts the same way as the sun during the day, simply with less total flux. Moonlight can directly illuminate the target, be scattered by the atmosphere, and be reflected by objects in the scene. Man-made sources such as streetlights, car headlights, and interior lights from buildings can also directly illuminate the target, be reflected off objects in the scene onto the target, or be scattered by the atmosphere toward the target or sensor. The scattering of man-made sources can be quite significant, particularly for large quantities of sources. This phenomenon is known as urban glow. Not all of these sources are consistently present in nighttime imagery, though. At even
lower illumination levels, the next significant sources include both starlight and chemical reactions in the upper atmosphere that produce photons, which is known as airglow.

There are many other sources of EM flux that can exist in a scene. Every object that has a temperature above 0 [K] emits energy, which interacts with the scene. For objects near room temperature, roughly 300 [K], there are very few photons emitted at visible and Near-IR (NIR) wavelengths. Hotter objects emit more photons in the visible and NIR, and can become significant sources for silicon detectors. The list of other man-made sources is extensive, and each contribute EM flux to the scene, but these are generally not significant from aerial remote sensing platforms as the signal is often lower than the noise of the sensing system.

### 2.1.2 Radiometry

The second part of the imaging chain is light interacting with objects in the scene before reaching the sensor. For a standard daytime scene, the light can follow a number of paths, as shown in Figure 2.1. Path A represents photons that travel from the sun directly to the target and bounce directly to the sensor. Path B photons are scattered by the atmosphere toward the target, then reflect off the target toward the sensor. This is the diffuse downwelled skydome radiance. Path C contains photons that reflect off objects in the scene and onto the target, then are reflected off the target toward the sensor. Some photons, such as path D photons, are scattered by the atmosphere directly toward the sensor and never reach the target. This is known as upwelled radiance. The radiance from each path is summed to determine the total radiance reaching the sensor.

There are infinitely-many more paths that photons can take that include multiple reflections off objects and multiple scatters by the atmosphere before they reach the target or the sensor. However, the flux along these paths gets smaller with each reflection or scatter. Energy along the path is lost to absorption into or transmission through a material, or scatter in a different direction. These additional paths that include multiple interactions become insignificant as the flux falls below the noise of the sensor system. Because sunlight is so bright during the day, the other photon paths not listed in Figure 2.1 are often ignored.
The same paths that existed for the sun during the day also exist for the moon at night. However, since the radiance values are much lower with moonlight than sunlight, other sources mentioned in Section 2.1.1 become significant. Figure 2.2 shows additional paths that become significant at night, which include: man-made sources in the scene (i.e., path E), starlight (i.e., path F), airglow (i.e., path G). Each of these sources also produces photons that scatter one or more times in the atmosphere before reflecting off objects in the scene and traveling to the target, the most significant being urban glow (i.e. path H). As with the multiple paths that sunlight takes toward the sensor, there are infinitely-many paths for these additional photons to take. For each scatter, reflection, and propagation through the atmosphere, there is an energy loss due to absorption or reflection away from the path of interest.

In the daytime example, with the four photon paths shown in Figure 2.1, the equation for radiance reaching the sensor in the reflective portion of the spectrum, as described in [37], would be:
2.1. THE IMAGE CHAIN

Figure 2.2: Significant photon paths in a nighttime scene.

\[ L(\lambda) = E_s \cos(\sigma) \frac{\tau_1(\lambda)r(\lambda)\tau_2(\lambda)}{\pi} + (FE_d(\lambda) + (1 - F)E_b(\lambda)) \frac{r_d(\lambda)\tau_2}{\pi} + L_u \]

or:

\[ L(\lambda) = L_s + L_d + L_b + L_u \]

where \( E_s \) is the exo-atmospheric solar irradiance, \( \sigma \) is the declination angle between the sun and zenith, \( \tau_1 \) is the transmission along the path from the sun to the target, \( r \) is the reflectivity of the target from the sun toward the sensor, \( \tau_2 \) is the transmission of the radiance from the target to the sensor, \( F \) is the percentage of the skydome visible to the target, \( E_d \) is the diffuse downwelled skydome irradiance from solar scattering, \( E_b \) is the diffuse background irradiance from reflections off scene objects, \( r_d \) is the diffuse reflectivity of the target, and \( L_u \) is the upwelled path radiance.

The first three terms can be rewritten where \( L_s \) is the solar radiance directly from the sun reflecting off the target to the sensor (i.e., Path A), \( L_d \) is the downwelled radiance from the sun scattered by the atmosphere towards the target then reflected to the sensor (i.e., Path B), \( L_b \) is the background radiance from the sun reflected off background objects to the target, then reflected to the sensor.
(i.e., Path C), and $L_u$ is the again the upwelled path radiance (i.e., Path D) [37].

For each transmission through the atmosphere and each reflection off an object in the scene, energy is lost to absorption or scattering off the initial path. Eq. (2.1) only accounts for the most significant sources of daytime radiance, but other sources and paths can be added to produce a more accurate final sensor-reaching radiance, particularly for nighttime scenes.

### 2.1.3 Optics

The optical system can be thought of as containing two processes: one spatial and the other radiometric. The optics focus the incoming light onto the detector, and take the sensor-reaching radiance and convert it to an irradiance onto the detector. Although no optical system is truly linear and shift-invariant (LSI), we can greatly simplify the mathematical model for the spatial effects of the optical system by making this assumption. Because of diffraction, the optical system can be treated as a low-pass filter, which removes high-spatial-frequency content and effectively blurs the image [12] [18]. Spatially, the output of the optical system can be treated as convolution of a optical Point Spread Function (PSF) with the scaled input image at the front of the optics.

This is done easily mathematically through the Fourier transform. The Fourier transform of the input radiance image can be modulated by the Modulation Transfer Function (MTF), which is the Fourier transform of the PSF. For incoherent light, the MTF is proportional to the auto-correlation of the spatial pupil function of the optics [18]. Since the PSF is dependent on wavelength, we must also assume that the light is quasi-monochromatic for this linear shift-invariant assumption to be valid. This means that the central wavelength of the light, $\lambda$, must be large compared to the spectral bandpass, $\Delta\lambda$ [12]. Therefore a different PSF should be applied at each narrow-wavelength band.

The equation for modeling the optical system is:

$$g(x, y, \lambda) = f(x, y, \lambda) * h(x, y, \lambda),$$

where $f(x, y, \lambda)$ is the scaled image at the front of the optics, $g(x, y, \lambda)$ is the output image incident
on the detector, and $h(x, y, \lambda)$ is the PSF of the optical system. The $*$ operator denotes convolution. Calculating the convolution operation is made easier via multiplication in the frequency domain:

$$\mathcal{F}\{g(x, y, \lambda)\} = G(\xi, \eta, \lambda) = F(\xi, \eta, \lambda) H(\xi, \eta, \lambda) = \mathcal{F}\{f(x, y, \lambda) * h(x, y, \lambda)\}. \quad (2.3)$$

$F(\xi, \eta, \lambda)$ is the Fourier transform of the input image, $G(\xi, \eta, \lambda)$ is the Fourier transform of the output image, and $H(\xi, \eta, \lambda)$ is the optical MTF. The MTF is proportional to the auto-correlation of the pupil function, and can be written as:

$$H(\xi, \eta, \lambda) \propto p(-\lambda f \xi, -\lambda f \eta) * p(-\lambda f \xi, -\lambda f \eta) \quad (2.4)$$

where $p(x, y)$ is the pupil function of the optics in space domain coordinates, $f$ is the focal length of the optics, and the $*$ operator denotes correlation. $H(\xi, \eta, \lambda)$ can then be normalized so $H(0, 0, \lambda) = 1$. Real optical systems add additional aberrations such as coma and astigmatism to the image, particularly off the optical axis. These aberrations, though, are not well modeled by a LSI system and will not be considered here.

For a circular aperture and incoherent light, the MTF resembles a circularly-symmetric triangle function with cutoff frequency at $
u_{\text{cutoff}} = \frac{d}{\lambda f}$, where $d$ is the optical aperture diameter, $\lambda$ is the wavelength, and $f$ is the focal length of the optics. Figure 2.3 show the MTF of such a system. The Fourier transform of the coherent MTF (i.e., the PSF) is the “sombrero” function, which is the 2-dimensional polar-coordinate analog of the SINC function. Like the SINC function, which is defined in relation to the sine function, the sombrero function is defined in relation to the first-order Bessel function of the first kind and is given by:

$$SOMB(\rho) = \frac{2 J_1(\pi \rho)}{\pi \rho} \quad (2.5)$$

where $\rho$ is the polar coordinate of the function, and $J_1$ is the first order Bessel function of first kind. For an incoherent light system with a circular aperture, the PSF is the $SOMB^2$ function, which is also known as the “airy disc” pattern. The first zero of the function at $1.22 \frac{\lambda f}{d}$, with $\lambda$
CHAPTER 2. BACKGROUND

Figure 2.3: Sample MTF of an incoherent circular-aperture optical system.

being the wavelength, \( f \) being the focal length, and \( d \) being the aperture diameter [12]. Figure 2.4 is an example PSF of an incoherent system. The PSF of this type of optical system, in polar coordinates, is given by:

\[
PSF(r) = \text{SOMB}^2 \left( \frac{r}{\lambda f d} \right)
\]  

(2.6)

Additionally, the optical system converts the energy from radiance reaching the sensor to irradiance on the focal plane. This relation accounts for the solid angle viewed by the system and is modeled by the G\# equation:

\[
G\# = \frac{1 + 4(f/\#)^2}{\tau \pi}
\]  

(2.7)

where \( f/\# \) is the f-number (i.e., the ratio of the focal length \( f \) to the aperture diameter \( d \)) of the
optical system, and \( \tau \) is the optical transmission. The G\# is a measure of how well the optical system converts from radiance to irradiance along the optical axis. The G\# equation is derived on page 154 of [37].

These equations are derived for a single-lens system, but most systems include multiple reflective or refractive elements. The same equations can be used for multi-lens systems or reflective optical systems by substituting in an effective focal length, \( f_{\text{eff}} \), and the effective f-number \( f\#_{\text{eff}} \) [37].

2.1.4 Detectors

The detector “link” converts an incident irradiance to a measurable signal in electrons, voltage, or digital counts. Most modern detectors are photo-sensitive semiconductors that absorb the energy of the incoming photons. If an incoming photon has the correct energy, \( E_g \), it causes an electron in the semiconductor crystalline lattice to be excited from the valence band, where it has energy \( E_V \), into the conduction band, where it has energy \( E_C \). An energy state diagram of this is shown in
Figure 2.5: Energy states of a semiconductor. $E_C$ is the energy state of electrons in the conduction band and $E_V$ is the energy state of electrons in the valence band [42].

Figure 2.5. If the electron reaches the conduction band, it has enough energy to move freely through the lattice. Charge carriers, either holes or electrons, can then be collected in a depletion region of a PN-junction in the semiconductor. The depletion region forms in an area where semiconductors with different doping characteristics are joined. Generally this is a positively-doped side (i.e., electrons have many free holes in the valence band to occupy) in contact with a negatively-doped side (i.e., there are excess free electrons in the conduction band). The free electrons from the n-doped side eventually occupy the holes in the p-doped side, creating a charge imbalance and therefore a voltage across the junction. The junction thus attracts and holds electrons and holes that are created by the absorption of a photon. Because of the high concentration of holes and electrons in the depletion region, the charge carriers created by absorbed photons discharge the junction, decreasing the voltage across it. The voltage change can be measured and is proportional to the number of generated carriers that were eventually held by the junction. Throughout this work we discuss the movement of electrons, but it is equally possible to discuss holes as the charge carrier. Electrons, though, generally have higher mobility in semiconductors, meaning that they have a larger chance of reaching the junction from a distance than do holes.

There are many factors that determine if the photon will be converted to a measurable signal.
2.1. THE IMAGE CHAIN

Figure 2.6: Energies needed to promote an electron for different dopants in silicon. The number listed is the energy difference between the energy level and either the conduction band, $E_C$, for levels above the gap center, or the valence band $E_V$ for levels below the gap center. Hollow bars indicate acceptor dopants and are the new energy level for the conduction band. Solid bars indicate donor dopants and represent the new valence band energy level [42].

The first is whether or not the photon is absorbed and creates an electron-hole pair. This is a function of the electron states in the semiconductor material, the wavelength of the incoming photon, and the thickness of the substrate. The electron states are determined by the doping characteristics of the semiconductor. The energy bandgap between the valence band and the conduction band in the substrate has a specific energy associated with it, $E_g$. An incoming photon needs that minimum amount of energy to be absorbed in the lattice and promote an electron to the conduction band. Different dopants alter the energy needed to promote electrons to the conduction band, changing the ability to absorb incoming photons at particular wavelengths. Figure 2.6 shows the different energies in [eV] needed by the incoming photons to promote electrons based of different potential silicon dopants. Some dopants reduce the bandgap by lowering the energy of the conduction band, $E_C$, generating extra holes. These are known as acceptor donors because they accept electrons. Other dopants reduce the bandgap by increasing the energy of the valence band, $E_V$, generating extra electrons. These are known as donor dopants as they add electrons.

If a photon promotes an electron and an electron-hole pair is created, it must travel to the depletion region and discharge the junction to be measured. The likelihood that the charge carrier reaches the depletion region is a function of the distance to the depletion region from the location the photon was absorbed and the diffusion length that the electron can travel before it is reabsorbed by the semiconductor.
Figure 2.7 shows the average depth where a photon will be absorbed in silicon as a function of wavelength. The shorter wavelength photons are usually absorbed in the first few nanometers of the substrate, while the longer wavelength photons are absorbed hundreds of microns from the irradiated surface. Because there is a minimum energy needed in a silicon detector to promote an electron to the conduction band, photons with wavelengths longer than roughly $1.05 \, \mu\text{m}$ pass through the semiconductor and are never absorbed. This wavelength limit, combined with the typical absorption depth of photons in silicon, means that the thinnest the silicon substrate can be and still be fully responsive to wavelengths up to the $1.05 \, \mu\text{m}$ wavelength cutoff is roughly $300 \, \mu\text{m}$ [6].

For the detector to measure the number of electrons excited by incident photons, the charge carriers must travel to the depletion region of the detector. This is done by diffusion, caused by like-charges repelling each other, or through an applied electric field. The mobility of carriers is a function of the doping characteristic of the semiconductor. Increasing the dopant level decreases the mobility, so carriers travel shorter distances before they are re-absorbed by the substrate.
2.1. THE IMAGE CHAIN

Figure 2.8: Typical mobility of electrons in silicon at 300 [K] for electrons, $\mu_n$, and holes, $\mu_p$ as a function of dopant concentration [42].

Figure 2.8 shows typical mobility, $\mu$, of carriers for different impurity concentrations in silicon at 300 [K]. As seen in the figure, the mobility of electrons, $\mu_n$, is higher than the mobility of holes, $\mu_p$. This means that electrons can travel farther in the substrate than holes over a given time period. Charge carriers, though, can diffuse as easily toward the junction as they can away from the junction or parallel to the junction. For this reason it is important that photons are absorbed as close as possible to or inside the depletion region. Charge that moves parallel to the incoming light causes pixel “cross-talk,” and results in blurring in the image. This is especially likely with a thick substrate where charge carriers must travel far to the depletion region. Applying an electric field across the thickness of the substrate can increase the likelihood of charge carriers moving to the correct pixel junction where the photon entered instead of to an adjacent pixel junction. This method is usually called “full-depletion” because it effectively extends the depletion region through the full thickness of the detector. A stronger electric field will result in less pixel cross-talk [5] [7].

The combined effect of the multi-step process of a photon being absorbed, generating a charge carrier, and that carrier reaching the depletion region is characterized by the Quantum Efficiency (QE). A single value for a detector’s QE is not an accurate measure because QE is a function of multiple sensor parameters, as well as the wavelength of the incoming photons. QE is usually quoted as a single value for each wavelength, but this is a statistically averaged value that in reality includes some variation about it. For the purpose of this work, we are not concerned about the
statistical variations in QE, and treat published values as a constant for each wavelength.

Once charge carriers reach the depletion region, they discharge the junction and can be measured. There are multiple types of readout designs, the most common of which are CCD-style readouts and CMOS-style readouts. CCDs collect the charge and read it out serially by passing the charges from one pixel to another, funneling them all to the same readout circuit. This is sometimes called a bucket-brigade method. A graphic of this method is shown in Figure 2.9. The charge is collected in each pixel, then it is passed up the columns in parallel to the last row. Charge is then read out in a serial fashion through measurement electronics. After the whole row is read out, each column passes the next row of pixel charges in parallel to the readout row, which is again read out serially.

CMOS sensors, on the other hand, have independent readout electronics for each pixel or small group of pixels. The charge at each pixel is read out in parallel through its own readout circuitry and charge is not passed between pixels.

The readout of any system introduces noise based on the design of the readout circuitry and the use of serial or parallel readout. The noise characteristics of these readout systems can be significantly different.

The final part of the detector system is a conversion from analog signal (generally voltage across a resistor) to digital counts in each image pixel. This quantization process also introduces noise into the system. Quantization of the signal to digital counts does not necessarily need to be performed linearly, and smart quantization techniques could lead to lower noise levels and a larger...
2.2 Low-SNR sensor systems

There are a few important differences between low-SNR nighttime systems and traditional daytime or bright nighttime systems. The two areas that this work addresses are modeling nighttime sources of scene radiance and modeling low-SNR silicon detectors. There can certainly be work done to improve other links in the chain for low-SNR systems, such as the throughput of the optics or new materials to sense at visible and NIR wavelengths, but those are not addressed here.

2.2.1 Low-SNR Sources

During the day, the sun is the dominant source of EM flux on the target. Typical direct solar illuminance values in the visible region with the sun directly overhead are on the order of \(10^5 \text{ lm/m}^2\). Typical downwelled solar diffuse (i.e., skydome) illuminance values are \(10^4 \text{ lm/m}^2\) [34]. With the exception of very energetic sources in the scene (e.g., fires), the sun and solar scattering are the only significant sources by a few orders of magnitude.

In a nighttime scene, the moon replaces the sun as a predominant source, and the prevalence and proximity of man-made sources makes them significant. For a full moon at zenith and a clear sky, the illuminance is approximately \(0.2 \text{ lm/m}^2\), and for a 33% crescent moon, approximately \(10^{-3} \text{ lm/m}^2\) [34]. Depending on the proximity of large cities, there can also be significant radiance from secondary sources, both in and out of the sensor Field-Of-View (FOV), that is scattered by the atmosphere toward the target. Particularly when the atmosphere is cloudy or hazy, there can be significant attenuation of moonlight, and significant urban glow. During times of the lunar cycle where only a small percentage of the earth-facing side of the moon is illuminated by the sun (less than a 33% crescent) and no man-made sources are in or near the scene, the combination of starlight and airglow become significant.

A list of sources and their contribution to illuminance on the target are shown in Table 2.1. This
is also shown graphically in Figure 2.10. The values listed in the figure and the table are in \( \text{[lm/m}^2\text{]} \), so only flux in the visible region is considered, with a bias toward green wavelengths. Sunlight, skylight, and reflected sunlight off the moon contribute the most flux at visible wavelengths and less flux in the NIR. Airglow, conversely, is nearly 10 times stronger at 1 \( \mu\text{m} \) than at 500 \( \text{nm} \) and relatively faint in the visible spectrum [20]. It is clear from the figure, though, that airglow and starlight become significant in the visible spectrum at night when the moon is near the horizon or is only a thin crescent. As with daytime scenes, the self-emission of photons by the earth and atmosphere due to their temperature contribute flux, but they are several orders of magnitude weaker than airglow in the visible and NIR spectrum.

Both airglow and urban glow have been extensively researched by the astronomy community. Astronomers have made several measurements of ground-reaching airglow and urban glow radiance from the sky-dome to try to remove these effects from telescope images looking out through the atmosphere. The spectrum of airglow and urban glow primarily consists of strong narrow-band emission lines at characteristic wavelengths, with an underlying weaker broadband emission. The bright emission lines from the upper atmosphere, in particular, can clutter spectral astronomical measurements. Light at those specific narrow-band wavelengths is typically filtered out to produce a clearer image of the sky beyond the atmosphere. Also of interest to astronomers is sensor spectral calibration. Well-characterized emission lines can be used as a tool to easily spectrally calibrate a telescope after it is fully installed and, more importantly, allow for periodic recalibration.

<table>
<thead>
<tr>
<th>Source</th>
<th>Approximate Illuminance [lm/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun @ zenith</td>
<td>100,000</td>
</tr>
<tr>
<td>Skylight on clear day</td>
<td>10,000</td>
</tr>
<tr>
<td>Skylight on overcast day</td>
<td>1000</td>
</tr>
<tr>
<td>Full moon @ zenith</td>
<td>0.2</td>
</tr>
<tr>
<td>Half moon @ 20° zenith angle</td>
<td>0.02</td>
</tr>
<tr>
<td>33% moon @ 60° zenith angle</td>
<td>0.003</td>
</tr>
<tr>
<td>Urban glow (variable)</td>
<td>0 to 0.2</td>
</tr>
<tr>
<td>Nighttime airglow</td>
<td>0.001</td>
</tr>
<tr>
<td>Starlight</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Table 2.1: Approximate integrated illuminance values in the visible region at the ground plane from typical natural sources [34].
2.2. LOW-SNR SENSOR SYSTEMS

Figure 2.10: Comparison of irradiance in $[\text{lm/m}^2]$ at the ground from natural sources as a function angle above the horizon [34].
2.2.1.1 Urban glow

Urban glow is the term for the light from large cities that is scattered by the atmosphere back down to earth. In an urban area, only the brightest stars are visible in the night sky due to the overwhelming flux from man-made sources that is scattered back down by the atmosphere. Each individual source, like a single streetlight or car headlight, scatters a very small amount of light onto a target a few kilometers away. However, since there are millions of lights in a typical large city, the aggregate flux scattered to a distant target is significant. Inside the city urban glow is even more significant, adding as much illuminance onto a target as the moon. Urban glow, commonly referred to as light pollution by astronomers, is a major area of research. Over the last decades, many astronomical sites have been negatively affected by the growth of cities, in some cases cities over 100 [km] away. Urban glow is a location-specific source of radiance and is a function of the distance from the target location to a city as well as the size of the city and the types of sources used [15] [39]. It is not always a significant source of radiance, but it can dominate a nighttime scene if large cities are nearby or the atmospheric conditions introduce significant scattering toward the target.

Much of the work that has been done to study urban glow is focused on correcting for it in astronomical images (i.e., subtracting it out of an image after-the-fact) or predicting the flux that will reach a given site[1][2][15]. The models that have been created have that goal in mind. Some are also used to predict the amount of urban glow at a site that might be used for a future observatory. These models are created to be approximations for thousands to millions of individual sources and applicable to a wide variety of cities, so they are not intended to have high fidelity. Instead they offer approximate radiance values at a fraction of the processing time needed to calculate urban glow using each source individually.

Many urban glow models are currently under development in the remote sensing community, but these are not yet well vetted or validated [39][28][29].
2.2.1.2 Airglow

Airglow is the release of photons by elements and molecules, primarily in the upper atmosphere, similar to the familiar aurora. Though unlike aurora, which has significant visible angular variation in the skydome and rapidly changes, airglow appears generally uniform. Aurora is caused by charged particles from the sun that interact with the Earth’s magnetic field and are deflected toward the polar regions. These energetic particles then excite molecules in the atmosphere which in turn release photons at characteristic wavelengths. Airglow, alternatively, is predominantly caused by high energy solar photons, which are not as influenced by the magnetic field, directly interacting with the atmosphere. The solar illumination on the upper atmosphere is generally uniform, but the atmosphere at high altitudes is not well mixed. The non-uniformity of airglow as seen from the ground is due to non-uniform mixing, variation in constituents at different locations, and motion of the particles. The altitude of airglow emissions is dependent on the constituents in the atmosphere and the density of the particles [11]. The intensity of the airglow can be different on different days and change throughout the day depending on the mixing, motion, and density of the constituents [46].

There are multiple reactions that can occur in the atmosphere to release a photon. These include:

- Chemiluminescence – particles join and form a compound with a lower energy state, releasing a photon.
- Resonance – a photon is absorbed and another emitted at the same wavelength.
- Fluorescence – a high energy photon is absorbed and one or more photons are emitted at longer wavelengths.

The number of photons released, and hence the overall intensity of the airglow, is primarily dependent on whether the upper atmosphere is directly illuminated by the sun. Daytime airglow is significantly brighter than nighttime airglow due to a higher percentage of solar photons that can excite the particles in the atmosphere [46]. During the day the scattering of sunlight by the
lower atmosphere is still orders of magnitude brighter and prevents the daytime airglow from being observed. Additionally, many of the constituents in the atmosphere go through diurnal cycles. The transition between daytime airglow and nighttime airglow is gradual since the upper atmosphere is in sunlight longer at higher altitudes. Oxygen and hydroxyls, which are the main contributor of nighttime airglow in the visible and NIR, follow this pattern. Nighttime airglow gradually diminishes after twilight and reaches a minimum roughly 6 hours after twilight [46]. As the density of atmospheric constituents change, so does the probability of characteristic photons being released. When the lower atmosphere is in the earth’s shadow during twilight and the upper atmosphere is still illuminated, the relative contribution of airglow to the total flux is greatest.

Resonance and fluorescence are the main processes of producing daytime airglow, and chemiluminescence is the dominant process for nighttime visible airglow [11]. Very high energy photons in the extreme ultra-violet are a main contributor of energy to excite electrons. Because airglow is caused by excitation from energy from the sun, its intensity follows the 11-year sunspot cycle, and it is influenced by solar events, similar to other phenomena in the ionosphere. The day-to-day and year-to-year fluctuation of nighttime airglow can significant, with the brightest recorded visible airglow emission being 2.5 times brighter than the weakest recorded visible airglow emission[46].

The majority of airglow emission is from particles in the upper atmosphere (i.e., roughly 30 [km] to 300 [km]) where the atmosphere is in non-local thermodynamic equilibrium, meaning that particles in the atmosphere can have drastically different energies. The collision rates of particle are lower at higher altitudes, so particles can hold their energy for a longer period of time and travel longer distances without releasing their energy [11].

Airglow is the emission of singular photons from individual particles, and these photons have a generally equal probability of being emitted in any direction. From the ground, a sensor would see the aggregate of photon emissions along the path through the atmosphere in a given direction. With the simplifying assumption that airglow emission from a particular constituent occurs in a uniform layer at a particular altitude in the atmosphere, the total number of photons reaching a target would be larger with longer path lengths through the emitting layer. Since the path length through any layer is longest at the horizon and shortest at zenith, the total number of photons
emitted toward the target is largest at the horizon. However, in the lower atmospheric layers where scattering is most prominent, the transmission loss is also strongest near the horizon, where the atmospheric path length is longest. Due to the combination of these two phenomena, the intensity of airglow as typically seen from the ground is strongest at a zenith angle of approximately $80^\circ$ \cite{23,45}. A graph of relative airglow radiance at the ground vs. zenith angle, $z$, is shown in Figure 2.11 for 530 nm light. $z = 0^\circ$ is at zenith, and $z = 90^\circ$ is at the horizon. The thick dashed line represents an average of 11 scans of the night sky from zenith to horizon taken at Mt. Haleakalā, Hawaii. Data from two of the 11 scans are shown as the thin solid lines. The thin spiked features in the individual scans are noted as inaccurate correction for bright stars in the sensor field-of-view \cite{23}.

Total illuminance on the ground from airglow and starlight is approximately the same as a 33% moon at $20^\circ$ above the horizon. Airglow contributes approximately 40% or more of the natural background light in the visible portion of the spectrum \cite{34}. Starlight accounts for 30% of the natural sky background, but much of this is from a few small point sources (i.e., the brightest few
star and planets). Since the location of stars and planets is well known, modeling these few sources as points in the skydome would account for the majority of the starlight incident on the target. Point source starlight, though, will not be considered here.

As with the sun, the lunar and starlight contributions are strongest in the visible spectrum, while airglow is strongest at longer wavelengths. Though airglow is stronger in the Long-Wave IR (LWIR) (i.e., 8–14 [µm]) than the SWIR (i.e., 1–3 [µm]), the LWIR is dominated by thermal self-emission from the atmosphere as well as reflected thermal energy from the earth’s surface. As seen in curve D of Figure 2.12, nighttime airglow is most significant between 1 [µm] and 2 [µm], where a gap exists between reflective lunar radiances and atmospheric thermal radiances [40].

Airglow shorter than 1 [µm] is caused predominantly by atomic oxygen (O) and hydroxyls (OH).
Figure 2.13: Airglow radiance at various altitudes for particular atmospheric constituents at their characteristic wavelengths [38].

Figure 2.13 shows a chart of nighttime airglow radiances at characteristic wavelengths as a function of altitude for various constituents. OH emissions are shown in the chart as the filled triangle and a hollow square. nighttime OH exists in a band at an altitude between and 50 and 100 [km], with the strongest emission layer around 85 [km] [4][11][38]. This is above the majority of the scattering layers of the atmosphere, so the airglow spectrum can be treated as being “exo-atmospheric” with regard to scattering.

Airglow, as viewed from a sensor on the ground pointed toward the skydome, is very faint in the visible and NIR, but the total contribution from the whole skydome can be significant, as listed in Table 2.1 and Figure 2.10. Because the contribution is so small over any small solid angle in the skydome, airglow is a negligible contributor to upwelled radiance in the visible and NIR for high-altitude systems that may be above the emitting layer.
2.2.2 Low-SNR Detectors

Standard daytime imaging systems used in nighttime scenes usually produce noise-dominated images. There are two general methods for improving the images: reduce the noise and collect as many photons as possible, or amplify the signal, which generally also amplifies the noise. If the moon is bright or there are significant secondary sources, many standard detectors used for daytime remote sensing can be used at night by simply extending the integration time to increase the signal. However extending the integration time is sometimes not feasible due to platform motion or object motion in the scene.

There are many types of detector systems that have been developed for low-SNR imaging systems, including:

1. CCD-CMOS Hybrids
2. Back-Illuminated CCDs
3. ICCDs
4. Avalanche Photodiodes
5. Multi-Anode Micro-channel Array (MAMA)
6. Wedge and Strip detectors
7. Precision Analog Photon Address (PAPA) detectors

Designs 1 and 2 represent systems that reduce the noise and collect as many photons as possible. Designs 3 and 4 amplify the signal, but at the same time also increase the noise. Designs 5-7 are non-imaging systems that attempt to count individual photons in extremely photon-starved conditions. Many of these detectors are discussed in greater detail in [25]. Each of these designs has specific trade-offs, and there is no one sensor that is ideal for all situations. This work will only address design types 1 and 2.

Most of the difference between fully-depleted back-illuminated CCDs and fully-depleted hybrids is in the readout circuitry.
2.2.2.1 Back-Illuminated CCDs

Traditional CCDs are made on a thick substrate with doping and gate structures added to the top side. Photons enter through the top side of the detector and create charge carriers when they are absorbed in the bulk substrate. The charge is then held in each pixel location by an electric field and read out serially in a “bucket brigade” fashion. The readout electronics measure the charge on the last pixel, then the charge from the other pixels is passed toward the readout pixel and read serially. The advantage of this system is uniform read noise since the system uses the same electronics to read out each pixel. However, this serial readout process is comparatively slow versus parallel readout, can loose charge during the transfer process, and often requires a shuttering mechanism so photons are not being absorbed while the charge is being read out from the previous exposure. Some CCDs do not require a shutter, and use a separate set of pixels for readout and collection. The exposed pixels collect charge, and the charge is passed as an image to the readout array quickly. Then the collection area can collect a new exposure as the charge from the previous exposure is read out.

A cross-section of a front-illuminated CCD is shown in Figure 2.14. When photons enter the front face of the CCD, some pass through the gate structure. While the gates are generally made with material that is transparent in the wavelengths where the detector is sensitive, the transmission is not necessarily spectrally uniform. Additionally, reflections off the gate structure can reduce the QE of the detector. Most silicon front-illuminated CCDs designed for use in the visible and NIR regions of the spectrum use gates that have lower transmission in the blue wavelengths than the rest of the spectrum. Consequently, the spectral sensitivity of the detector at these wavelengths is decreased.

A solution to the transmission problem is to illuminate the CCD from the back side. This means that the substrate must be thin enough for the charge carriers to diffuse to the pixel depletion region where they can be measured. Thicknesses of most back-illuminated CCDs are on the order of 10 to 100 [µm]. This is usually too thin for standard manufacturing techniques, so back-illuminated CCDs are often manufactured on thick substrates and the back side is etched
Figure 2.14: Diagram of a typical front-illuminated CCD with a low-resistivity p+ substrate, higher resistivity p- epitaxial layer, n-doped buried channel, and poly-silicon gate structure [30].

away to the appropriate thickness. Since the illuminated surface is etched, it is difficult to get it smooth and uniform. The surface imperfections, or “traps”, prevent photons that are absorbed near the surface from easily diffusing to the junction. A diagram of a thin back-illuminated CCD is shown in Figure 2.15. Another problem with thin detectors is that fringing can occur due to internal reflections. For long wavelength light, the absorption depth is longer than the substrate is thick. The internal reflection of these photons off the back surface can lead to fringes in the resulting imagery [19].

To keep noise low and charge transfer efficiency between pixels high, a uniform region is needed where charge is collected and held. Front-illuminated CCDs are still generally preferred for most applications because they are easier, and thus cheaper, to manufacture. Manufacturing a thin substrate is problematic because it is not as durable and leads to lower yields.

New sensors have been developed that incorporate the advantages of both thin, back-illuminated CCDs and front-illuminated CCDs. Lawrence Berkeley National Laboratory (LBNL) has developed a fully-depleted back-illuminated CCD that has high QE at all wavelengths, low cross-talk, and low noise for use in low-SNR systems. QE can be increased even further with the addition of a transparent anti-reflective coating on the illuminated back surface. This coating can be tuned to
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Figure 2.15: Diagram of a thin back-illuminated CCD that improves QE because the photons do not pass through the gate structure [30].

improve QE in any part of the sensor spectral band [22]. A figure of the basic design is shown in Figure 2.16.

2.2.2.2 CCD-CMOS Hybrid sensors

CCD-CMOS hybrid sensors take the parallel nature of the CMOS readout and add the high fill factor and QE of a traditional CCD. These hybrids are actually two semiconductor substrates that are bonded together to take advantage of the best qualities of both sensor designs. One material often used for bonding the substrates is indium since it is a good conductor and somewhat malleable, offering a good connection and durability. Charge carriers are generated in the bulk substrate similar to a CCD, but the charge is passed vertically through the indium bumps to the CMOS readout on a second substrate below. An illustration of a hybrid detector is shown in Figure 2.17. As with the CCDs discussed above, the thickness of the detector array and the anti-reflective coating on the illuminated surface are responsible for the QE of the sensor. Since the hybrids are 2 different substrates bonded together, their characteristics can be optimized for either the photo-detection or readout tasks [5].

Advantages include:

• Higher sensitivity at short wavelengths than traditional CCDs because of smooth front surface
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Figure 2.16: Diagram of a fully-depleted back-illuminated CCD on highly-resistive n-doped silicon [30].

Figure 2.17: Illustration of a hybrid detector showing the incoming light on the detector, the indium bonds that move the charge to the Readout Integrated Circuit (ROIC), and the Printed Circuit Board (PCB) on which the detector is mounted [33].
and no transmission loss through gates

• Low-power and high-frame-rate from parallel nature of CMOS readout

• Potential for increased thickness for better spectral sensitivity at long wavelengths

• Full-pixel fill-factor leads to higher QE than traditional CMOS sensors

• No need for mechanical shutter because of parallel readout

Major disadvantages include the manufacturing difficulty and cost of creating the two substrates and bonding them together.

Teledyne Imaging Sensors (formerly Rockwell Scientific) [6] [5], and Fairchild Imaging [32] are both developing hybrid sensors for low-SNR imaging.

2.3 Modeling

2.3.1 Current DIRSIG capabilities

When designing a new system or studying the effects of specific parameters on overall system performance, it is often prohibitively expensive and time consuming to run many test cases on real scenes with actual sensors. Using a simulated environment that accurately models the image chain is generally faster and cheaper. It also offers the flexibility to adjust parameters individually and quickly without affecting other sensor parameters. This allows for quick and accurate trade studies without large build costs and testing costs. Moreover it provides a capability for trade studies to be conducted with new materials or designs that may not be currently fielded or may not yet exist. This flexibility makes sensor system modeling a great tool for research and future sensor development, and it adds a tool for validating the performance of a newly built system.

DIRSIG incorporates the first few elements of the image chain as discussed in Section 2.1. It accounts for the sources of EM flux in the scene, the correct radiometry to account for the propagation of the flux through the scene to the sensor, and simple detector geometry information
(e.g., detector size and focal length) to allow it to produce an oversampled radiance field image at the sensor plane. It also has a sensor model that can add MTF effects to a simulated image.

Before this work, the available sources of radiance for a nighttime scene in DIRSIG included the moon, scattered moonlight, secondary sources (e.g., streetlights, headlights, and interior building lights), and background “starlight”. An illustration of the sources and sensor paths that were modeled in DIRSIG before this work is shown in Figure 2.18. Moonlight and scattering from the moonlight are handled by the “Moderate Spectral Resolution Atmospheric Transmittance Algorithm and Computer Model” (MODTRAN), code developed by the Air Force Research Lab (AFRL) and Spectral Sciences, Inc. (SSI) [10]. Secondary sources in the scene are included in target-reaching radiance calculations, but atmospheric scattering from these sources is not considered. The starlight distribution before this work was a coarsely sampled spectrum that was incorrectly distributed angularly in the skydome. A Red-Green-Blue (RGB) color image of that background skydome as seen from the target location looking up at the sky is shown in Figure 2.19. The center of the circle represents zenith and the outside edge of the circle represents the horizon along each azimuthal direction. The figure shows that the intensity is highest at a $45^\circ$ zenith angle, not at $80^\circ$ where it should be to match empirical data [23]. This starlight radiance does not interact with the atmosphere before reaching the target. This means that there is no accounting for changes in the atmosphere or path length through the atmosphere. The background “starlight” is meant to represent all sources of background radiance in the skydome, including both airglow and starlight. Airglow, urban glow, and bright stars were not modeled correctly in DIRSIG, but can contribute to target-reaching radiance in a real scene as discussed in Section 2.2.1.

There are two ways to incorporate radiance into a DIRSIG scene. The first is to include the source radiances in an Atmospheric Database (.ADB) file, which is what DIRSIG uses to determine radiance values in the skydome from different directions, and the second is to include secondary sources directly in the DIRSIG scene. The secondary sources in the scene are specified to have a given size and spectral distribution with known intensity. They do not interact with the atmosphere (e.g., scattering, transmission loss) until they are reflected off the target. More information on the incorporation of secondary sources can be found in the DIRSIG User’s Manual [10].
2.3. MODELING

Figure 2.18: Sensor paths for a nighttime scene that are currently modeled in DIRSIG.

Figure 2.19: RGB image of the old implementation of background radiance in DIRSIG. This is what a zenith-looking sensor would see when positioned at the target location on the ground. The center of the image is at zenith and the edge of the circle is the horizon.
There are three ways to incorporate radiance into the ADB files. The first two are generated automatically by a DIRSIG program called `make_adb`, and include a direct output from MODTRAN and the spectral background file. Since the ADB file is a text file, as a third option it can be manipulated manually. The `make_adb` code calls multiple runs of MODTRAN and uses the outputs to generate a text file that includes the direct, downwelled diffuse, and upwelled radiances in the scene (i.e., $L_s$, $L_{sd}$, and $L_u$ in Eq. (2.1)) from either the sun during the day or the moon at night. The direct term is along the path from the sun or moon to the target, and the upwelled terms listed in the ADB file are along the path from the target to the sensor. The downwelled radiance terms are generated from 72 runs of MODTRAN with the sensor at the target location looking up at the skydome at each of 12 azimuth angles (i.e., every 30°) and 6 zenith angles (i.e., every 15° starting at 7.5°). The `make_adb` program also adds a background spectrum to the downwelled target-reaching radiance, which is read from an external text file. The background skydome is shown in Figure 2.19, and is added to all scenes by default.

### 2.3.2 DIRSIG improvements

This project adds the most significant sources of target-reaching radiance that are not currently in DIRSIG into the nighttime model, namely urban glow and a more accurate airglow/starlight radiance.

In the remote sensing community, AFRL and SSI have been working on both measuring and modeling specific concentrations of particles in the atmosphere and the specific radiances and altitudes of airglow. These measurements have led to the Synthetic High-Altitude Radiance Code (SHARC) [3] that models IR airglow from 1–40 [$\mu$m]. SHARC has been combined with MODTRAN into one unified code, SHARC And MODTRAN Merged (SAMM), whose outputs are similar to MODTRAN but include airglow effects. A proposed future improvement to DIRSIG that is not done as part of this work is to use SAMM in place of MODTRAN. This will add airglow to both the downwelled and upwelled radiance terms in Eq. (2.1). Chapter 6 discusses the implementation of SAMM into DIRSIG.
Extension of the SHARC and SAMM codes below 1 [µm] is ongoing work at AFRL and SSI [8]. Since the visible and NIR components of airglow cannot yet be incorporated in a unified code, empirical measurements of the skydome from the astronomy community [20] are used as additional sources of target-reaching radiance in the DIRSIG scenes in this work.

Scattered light from large cities in or near the sensor FOV, known as urban glow, is another source of light that makes significant contributions in the visible and NIR. Before this work, DIRSIG did not account for scattering from secondary sources because of the processing time required and limitations of MODTRAN. Like airglow, urban glow has also been extensively researched in the astronomy community to study how astronomical sites are degraded by light from distant cities [15][16][46]. Numerous models have been created to predict the radiance that will reach the telescope due to urban glow [1][2][28][29][39]. We can use these models to predict the target-reaching radiance from urban glow in DIRSIG scenes and add the value to the downwelled radiance reaching the target in the ADB file.

One model that has been well accepted and validated in the astronomy community was created in 1986 by R. H. Garstang at the Joint Institute for Laboratory Astrophysics in Boulder, CO [15], and has been improved, validated, and updated [16][17] since its initial publication. It has been used to predict future urban glow radiances at existing astronomical sites as well as predict which locations have appropriate urban glow levels to build new telescope sites. This model was chosen in this work because it is well documented and validated. The model is implemented in Matlab, and the resulting radiances are incorporated into DIRSIG through the ADB file.

2.3.3 Garstang’s urban glow model

2.3.3.1 Basic model

R. H. Garstang’s model is designed for the astronomy community, but can be easily extended to remote sensing models such as DIRSIG. The model determines the downwelled radiance values at the target from a given sensor geometry. The original model created in 1986 [15] set the majority of the framework, and the geometry was later improved upon in 1989 [16] and 1991 [17]. The basic
model assumptions include an atmosphere with a uniform mix of constituents and a molecular density that degrades exponentially with altitude. The only atmospheric parameter that can be changed in the model is the ratio of aerosol scattering to molecular scattering, which appears in the model as the parameter $K$. The complete derivation of the radiometry can be found in Garstang’s publications [15] [16] [17], so here we will only discuss the equations needed for implementation.

The basic geometry of the original 1986 model is shown in Figure 2.20. It assumes a circular city centered at $C$ with radius $R$. The target site (i.e., the telescope location in the original model) is at $O$, which is at elevation $A$ above, and distance $D$ away from the city center. For every azimuth angle, $\beta$, and zenith angle, $z$, there is a small solid angle along the ray $\overrightarrow{OQ}$ in which light from the city is scattered toward $O$. For each small volume in the solid angle $\delta$ at point $Q$, the model integrates all the flux scattered toward $O$ from every point, $X$, in the city. The sum of all the flux scattered toward $O$ from all small volumes along the ray $\overrightarrow{OQ}$ is the total radiance that reaches the target, which Garstang calls $b(\beta, z)$. The transmission loss along the path length, $s$, from $X$ to $Q$, and the transmission losses along the path length, $u$, from $Q$ to $O$ are also incorporated.

The basic equation for the intensity of the light from $X$ toward $Q$ is given as:

$$I_{up} = \frac{LP}{2\pi} \left[ 2G(1 - F) \cos(\psi) + 0.554 \cdot F \cdot \psi^4 \right] \quad (2.8)$$
where $L$ is the number of lumens per person in the city, $P$ is the population of the city, $F$ is the fraction of light that is radiated directly into the sky at angles above horizontal, and $G$ is the reflectivity of the ground below the light sources. A value of $L = 1000$ lumens per person in the city was used as a basis for the model. This value was found to produce radiance estimates that closely match actual measurements. The model assumes that the vast majority of light pollution comes from street lights, which are generally positioned over concrete and asphalt roads and parking lots. The first term in the brackets represents the reflected light off the ground and the second term represents light directed upward from the source. $G$ is set to a nominal reflectivity of concrete and asphalt, at $G = 15\%$. $G = 60\%$ is quoted for ground that is snow covered. The reflections off the ground are assumed to be Lambertian, and the value of $\psi^4$ is used to model the fact that more direct light from the source radiates upward at angles near horizontal (i.e., close to $\psi = 90^\circ$) than straight vertical or at moderate angles. The scale factors are appropriate to give correct normalization when $I_{up}$ is integrated over the full hemisphere.

The transmission along the path from $Q$ to $O$ is:

$$\tau_{QO} = \exp \left( -N_m\sigma_R \exp(-cH) \cdot p_{QO} \sec(z) \right)$$

where:

$$p_{QO} = c^{-1} (\exp(-cA) - \exp(-ch)) + 11.778K \cdot a^{-1} (\exp(-aA) - \exp(-ah))$$

where $N_m$ is the molecular optical density, $\sigma_R$ is the Rayleigh cross sectional area, and $c$ and $a$ are scale parameters based on empirical measurements. $K$ is the ratio of Rayleigh to aerosol scattering. Similarly, the transmission along the path from $X$ to $Q$ is:

$$\tau_{XQ} = \exp \left( -N_m\sigma_R \exp(-cH) \cdot p_{XQ} \sec(\psi) \right)$$

where:

$$p_{XQ} = c^{-1} (1 - \exp(-ch)) + 11.778K \cdot a^{-1} (1 - \exp(-ah))$$

The model accounts for double scattering where the second scattering occurs at $Q$. This can
be considered an adjacency effect as photons from the city at points other than X are scattered into the path toward O at Q and then subsequently scattered to O at Q. The double scattering in the model adds flux to the total energy reaching Q and is defined as:

\[
S_d = 1 + \frac{N_a \sigma_a (1 - \exp(-a \cos(\psi)))}{a \cos(\psi)} + \frac{\gamma N_m \sigma_R \exp(-cH) (1 - \exp(-c \cos(\psi)))}{c \cos(\psi)}
\] (2.11)

where \( N_a \) and \( N_m \) are the aerosol and molecular optical densities, \( \sigma_a \) and \( \sigma_R \) are the aerosol and Rayleigh cross sectional areas, and \( \gamma \) is a scale factor that was empirically derived to be \( \frac{1}{3} \). Since \( S_d \) is a multiplicative term in the final radiance equation, the first term in Eq. (2.11) represents the single scattering term, and the second and third terms are proportional to the single scattering values. The second term in Eq. (2.11) is for aerosol double scattering, and the third term is for molecular double scattering.

To make calculations simpler, a factor \( K \) is used to model the aerosol scattering in the atmosphere as a function of the molecular scattering, which is assumed constant at a given altitude for all cases. The relationship defining \( K \) is:

\[
N_a \sigma_a = 11.11K \cdot N_m \sigma_R \exp(-cH)
\] (2.12)

The factor 11.11 was chosen so \( K = 1 \) is appropriate for a clear atmosphere at sea-level.

The basic equation for the total radiance reaching the target at O from the direction defined by \( \beta \) and \( z \) is:

\[
b(\beta, z) = \pi N_m \sigma_R \exp(-cH) \int_0^{\frac{L_{up}}{\pi R^2}} \tau_{XQ} \tau_{QO} S_d \left[ \frac{\exp(-ah)3(1+\cos^2(\theta+\phi))}{10\pi} + \exp(-ah) \right] 11.11K \cdot f(\theta + \phi) \] \] (2.13)

where \( \frac{L_{up}}{\pi R^2} \) is the radiance from the city at point X toward Q. \( \tau_{XQ} \) and \( \tau_{QO} \) are the transmission terms from X to Q and Q to O, respectively. \( S_d \) is the double scattering term, and the expression
in the brackets is the scattering coefficient for both molecular scattering (first term) and aerosol scattering (second term). The integral from 0 to $\infty$ covers all path lengths, $u$, (and thus all points, $Q$) along the ray $\overrightarrow{OQ}$. The double integral is for all points in the city, $(x, y)$. $\frac{1}{\pi R^2}$ is the scale factor for the city size, and the terms in front of the double integral are part of the scattering function but are brought out of the integral because they do not depend on the variables of integration: $u$, $x$, and $y$. The aerosol density term, $N_a$, and aerosol cross section term, $\sigma_a$ from Eq. (2.11), are replaced in Eq. (2.13) by the relation containing factor $K$ from Eq. (2.12), greatly simplifying the integral.

The constants $N_m$, $\sigma_R$, $c$, $a$, and the function $f(\theta)$ are all derived from empirical measurements. The values Garstang uses for the model are:

- Sea-level molecular optical density: $N_m = 2.55 \times 10^{-19}$ [cm$^{-3}$].
- Rayleigh scattering cross section: $\sigma_R = 4.6 \times 10^{-27}$ [cm$^2$].
- Molecular scale height: $c = 0.104$ [km$^{-1}$].
- Aerosol scale height: $a = 0.657 + 0.059K$ [km$^{-1}$].
- Aerosol scattering function:
  \[
  f(\theta) = \begin{cases} 
  7.0 \exp(-0.2462\theta); & 0 \leq \theta \leq 10^\circ \\
  0.9124 \exp(-0.04245\theta); & 10^\circ < \theta \leq 90^\circ \\
  0.02; & 90^\circ < \theta \leq 180^\circ 
  \end{cases}
  \]

2.3.3.2 Upgrades to Garstang’s model

There are a few drawbacks to this original model that are addressed in the 1989 and 1991 updates. The first is that very bright cities that are “far” from the target can be significant sources of radiance, but the flat-earth geometry in the model becomes inaccurate. To account for this, the geometry was changed to a round-earth model and is shown in Figures 2.21 and 2.22. There are two situations that can result from this change in the model. The first case shown is when the target, $O$, is above the line tangent to the earth in the plane of the city, as in Figure 2.21, and the second case is when the target is below the tangent line of the city (i.e., the earth’s curvature obscured some of the light from reaching the sky just above the target), as in Figure 2.22.
CHAPTER 2. BACKGROUND

Figure 2.21: Garstang’s 1989 model accounting for a curved earth when the target is above the city plane [16].

Figure 2.22: Garstang’s 1989 model accounting for a curved earth when the target is below the city plane [16].
2.3. MODELING

The updates to the model are a round-earth geometry, a better aerosol scattering function, and better approximations for path transmission and double scattering based on the new geometry. The definitions remain mostly the same as for the 1986 model. A city is centered at \( C \) at an altitude \( H \) above sea-level and surface distance \( D \) to an observation point at \( O \) which is at an altitude \( A \) above the altitude of the city. The total distance from the center of the earth to \( C \) is \( E + H \), where \( E \) is the radius of the earth at sea level. The total height from the center of the earth to \( O \) is \( E + H + A \). The new term for the distance from the center of the earth to the scattering point \( Q \) is \( E + H + h \). An additional angle term is needed for the angle subtended by the arc from \( C \) to \( B \) and is defined as \( \chi = \angle BSC \) where \( S \) is the center of the earth.

Another consequence of the new geometry is that the limits of integration along \( u \) are not always 0 to \( \infty \) since parts of the city may be obscured by the earth at some locations of \( Q \) in scenes such as what is shown in Figure 2.22. All volumes along \( OQ \) from \( O \) out to a distance \( u_0 \) are obstructed from the city by the earth. In this case the new limits of integration are \( u_0 \) to \( \infty \). For the case in Figure 2.21, the integration remains 0 to \( \infty \). The choice of which limits to use is based on the calculation of the distance \( w \) in Figure 2.22, which is the distance from \( O \) to \( W \) and is defined geometrically as:

\[
w = 2(E + H) \cdot \sec(\chi) \cdot \sin^2 \left( \frac{\chi}{2} \right) - A
\]  

(2.14)

By this convention, \( w \) is positive if \( W \) is above \( O \). If \( w \) is positive, we integrate from \( u_0 \) to \( \infty \), otherwise from 0 to \( \infty \). The integration limit, \( u_0 \), is defined as:

\[
u_0 = \frac{2(E + H) \cdot \sin^2 \left( \frac{\chi}{2} \right) - A \cos(\chi)}{\sin(z) \cos(\beta) \sin(\chi) - \cos(z) \cos(\chi)}
\]  

(2.15)

The new height of the scattering volume at \( Q \) is approximated to second order as:

\[h = A + u \cos(z) + \frac{u^2 \sin^2(z)}{2(E + H)}
\]  

(2.16)

The new extinction factors, \( \tau_{XQ} \) and \( \tau_{QO} \), must also be redefined for the new geometry. They
\begin{equation}
\tau_{QO} = \exp \left( -N_m \sigma_R \exp(-cH) \left( p_1 + 11.78K \cdot p_2 \right) \right)
\end{equation}

where:

\begin{align*}
p_1 &= c^{-1} \exp(-cA) \sec(z) \\
&\quad \cdot \left( 1 - \exp(-cu \cos(z)) + \frac{\epsilon \tan^2 \frac{z}{2}}{2 \pi} \left[ \left( c^2 u^2 \cos^2(z) + 2cu \cos(z) + 2 \right) \exp(-cu \cos(z)) - 2 \right] \right)
\end{align*}

and:

\begin{align*}
p_2 &= a^{-1} \exp(-aA) \sec(z) \\
&\quad \cdot \left( 1 - \exp(-au \cos(z)) + \frac{\epsilon \tan^2 \frac{z}{2}}{2 \pi} \left[ \left( a^2 u^2 \cos^2(z) + 2au \cos(z) + 2 \right) \exp(-au \cos(z)) - 2 \right] \right)
\end{align*}

The scale factor, \( \epsilon = \frac{16}{3\pi} \), is a normalization factor, and all remaining constants and variables are defined as before in Section 2.3.3.1. Eq. (2.17) is undefined when \( z = 90 \). For this special case:

\begin{align*}
p_1 &= \exp(-cA) \left( u - \frac{cuv^3}{6s(E+H)} \right) \\
p_2 &= \exp(-aA) \left( u - \frac{cuv^3}{6s(E+H)} \right)
\end{align*}

Eqs. (2.17) and (2.18) can be used for \( \tau_{XQ} \) by changing all variables of \( z \) to \( \psi \), changing \( u \) to \( s \), and setting \( A = 0 \). A new double scattering equation is also introduced, which corrects Eq. (2.11) above. The new equation is:

\begin{equation}
S_d = 1 + (11.11K \cdot f_2 + \gamma f_1) N_m \sigma_R \exp(-cH)
\end{equation}

where \( f_1 \) and \( f_2 \) are the same as \( p_1 \) and \( p_2 \) from Eq. (2.17) with the change of \( z \) to \( \psi \), \( u \) to \( s \), and \( A = 0 \). As with the original doubles-scattering term, \( \gamma = \frac{1}{3} \) to match empirical data. The flux reaching \( O \) is found using Eq. (2.13) as in the original model with the new terms and integration limits.

Additional modifications have been made to this model by Garstang to account for dust layers in the atmosphere and to incorporate a natural sky background. These will not be addressed in the current work but are possible areas for future enhancements.
2.3. SENSOR MODEL

The sensor system takes an aperture-reaching radiance image and converts it to a digital count image. This process, discussed in Sections 2.1.3 and 2.1.4, involves spatial “blurring” by the low-pass operation of the optics, conversion of aperture-reaching radiance to focal-plane irradiance, spatial sampling by the detector, quantum conversion of photons to electrons, and quantization to digital counts.

As mentioned in Section 2.1.3, the spatial “blurring” by the optics can be modeled as convolution between the scaled image at the front of the optics and the PSF. For an incoherent system, which is the case for almost all passive remote sensing systems, the PSF is given by Eq. (2.6). This is $h(x, y)$ in our system equation given in Eq. (2.2). The output of DIRSIG is an oversampled aperture-reaching spectral radiance. This is $f(x, y)$ in our system equation. The output, $g(x, y)$, is spatially the input image incident onto the detector. The focal length, $f$, and wavelength, $\lambda$, are set for any DIRSIG image, so the only parameter that can be changed in an external model for the PSF is the aperture diameter, $d$. As the aperture diameter increases, higher spatial frequencies are passed through the system, so the PSF gets smaller and there is less blur. Figure 2.23 shows a sample PSF for both a large (a) and small (b) aperture system.

Figure 2.23: Sample PSFs for different sized apertures. (a) represents a larger aperture than (b).
Secondly, the optical system accounts for the solid angle viewed by the sensor and converts an aperture-reaching radiance in [W/(cm²·sr)] to an irradiance incident on the detector in [W/cm²]. This is done through the G# given in Eq. (2.7). As was the case with regard to MTF effects, the only free parameter in the G# equation is the f/#. Since the focal length is fixed by DIRSIG, the aperture diameter is the only free parameter that the external model can adjust for a given image. In this case a larger aperture means the system collects more photons, which increases the irradiance on the detector for a given radiance at the aperture.

In order to calculate the quantum conversion from photons to electrons, the model must convert from power [W] to photon flux [photons/s]. The relationship between power and photon flux is given by:

\[ \Phi[W] = \frac{Q}{t} \left[ \frac{J}{s} \right] = \frac{hc}{\lambda} \cdot \frac{P}{t} \left[ \text{photons} \right] \]

where \( \Phi \) is the power in watts, \( Q \) is energy in joules, \( t \) is time in seconds, \( P \) is the number of photons, \( \lambda \) is the wavelength of the light in meters, \( c \) is the speed of light in meters per second, and \( h \) is Planck’s constant, which is equal to \( 6.626 \times 10^{-34} [J \cdot s] \).

The sensitivity of the detector in converting photons to electrons, QE, is a function of:

- Semiconductor material
- Wavelength of incoming photons
- Detector temperature
- Level of semiconductor doping
- Diffusion length of carriers in the material
- Absorption depth of photons
- Substrate thickness
- Exposed photosensitive area
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- Voltage across and area of depletion region

QE is a function of wavelength and can be calculated based on the above parameters. As mentioned in Section 2.1.4, it is usually measured for a given system because the calculations are based on statistical likelihoods. Each step in conversion from incident photons to collected electrons has an error associated with it. For this project the QE of the detector will be taken from published measurements. Calculating the QE from detailed systems parameters is an area for future improvement.

With regard to spatial imaging, one drawback to a small f/# system is that the light is incident on the detector at angles that deviate significantly from the normal to the surface. Because the absorption depth in the detector is often larger than the pixel pitch for long wavelengths, photons that are incident on the detector at large angles from the surface normal can cause the photons to be absorbed in a neighboring pixel from where it is focused. This angle is increased as f/# decreases. A graphic of this is shown in Figure 2.24. Detectors that have a wider depletion region suffer from the effect more than those with a small depletion region. If the photon enters at a larger incident angle and is absorbed deep into the substrate, it is farther laterally from the pixel on which it was focused. The farther the depletion region extends into the substrate the more likely it is that the pixel will be measured by the system. This uncertainty of where the photon is absorbed requires a more sophisticated model than what is developed for this project. With high-resistivity silicon, the index of refraction is high, which helps “straighten out” the light as it enters the substrate before it is absorbed. These depth of focus issues become most problematic for “small” f/# systems but are not as significant for larger f/# systems [7]. For the full-depleted back-illuminated CCDs model in this work, depth of focus spreading is not significant for f/# larger than f/1.3 [19].

Spatially, the detector can have pixel cross-talk, where some photons that strike one pixel are recorded as electrons in adjacent pixels due to lateral diffusion of the carriers in the substrate. Additionally there can be capacitive-coupling between adjacent pixel readouts that can cause cross-talk. These spatial phenomenon can also be modeled by a PSF and the linear system approach
discussed in Section 2.1.3. Different readout technologies suffer from cross-talk in different ways. There is more capacitive-coupling cross-talk with CMOS sensors than CCD sensors because of the parallel nature of the electronics, but work has been done to fully remove these cross-talk effects from CMOS imagers [33]. The cross-talk between pixels in a CCD sensor is often different in each direction (i.e., the cross-talk is near zero in the “cross-readout” direction and could be significant in the “along-readout” direction). This is caused mostly by carrier diffusion in the substrate, and is mitigated by the full-depletion of the detector [5] [41]. This energy spread in the detector requires a more sophisticated sensor QE model and has been largely mitigated by advances in the technology, so it is not addressed in this work.

2.3.5 Noise

The main sources of noise to consider in a typical low-SNR systems are:

- Shot noise (photon noise) that comes from the uncertainty of the arrival rate of photons on the detector and is modeled as a Poisson distribution. This noise is unavoidable, so it defines the absolute lower limit of detector noise.
- Dark noise that comes from the temperature of the semiconductor. Minority carriers are created in the substrate by the thermal energy of the detector much the same way as a photon. This causes the depletion region of the detector to slowly discharge over time even when not exposed to photons. The discharge is measured by the readout electronics and is indistinguishable from the discharge of the junction due to photon absorption. The thermally generated electrons are known as dark current and add a bias to the resulting image when read out. Due to the quantum nature and uncertainly of the generation rate of these dark current electrons, the dark noise is also modeled by a Poisson distribution with the mean being the dark current. Dark current is a function of both temperature and bias voltage across the PN-junction. It is often measured for a detector and quoted in electrons per pixel or amps per square centimeter.

- Read noise which is often caused by the transistors used to measure the signal. This is modeled as either Johnson noise (“white” noise), or flicker noise (“1/f noise”), depending on the readout sampling rate of the detector. Johnson noise is caused by the random motion of the carriers, and flicker noise is caused by imperfections in the substrate. These imperfections, or “traps” can cause carriers to get “stuck” for variable amount of time, affecting the measured voltage during readout. Flicker noise is often higher than Johnson noise, but is highest at low readout frequencies. It can be effectively eliminated by smart sampling techniques such as correlated double sampling [24]. Read noise is usually measured for a detector and quoted in electrons.

- Quantization noise that comes from the uncertainty of the number of actual electrons that were quantized to a particular digital count output. This is a function of the Quantum Step Equivalent (QSE) (i.e., how many electrons are counted as one digital count) of the system. If the QSE is high, there is more uncertainty what the actual number of charge carriers was than if the QSE is low.

For this work we assume a statistical model for the noise. In a low-SNR environment, particularly when shot-noise-limited (i.e., photon counting), the noise in the system might not be well-modeled
by statistics. Unfortunately more sophisticated noise models are beyond the scope of this project,
so statistical noise is used here with the caveat that it is not necessarily ideal for low-SNR scenes
and sensors. For most low-SNR systems, including the state-of-the-art imaging sensors modeled
in this work, either read noise or dark noise dominates shot noise.

Noise terms in the system tend to add in quadrature, so the total root-mean-squared (RMS)
noise in the systems is modeled as:

$$\sigma_{RMS} = \sqrt{\sigma_{shot}^2 + \sigma_{dark}^2 + \sigma_{read}^2 + \sigma_{quant}^2}$$  \hspace{1cm} (2.21)

where $\sigma_{RMS}$ is the overall system noise, which is modeled as the standard deviation of a normal
distribution. $\sigma_{shot}$ is the shot noise, $\sigma_{dark}$ is the dark noise, $\sigma_{read}$ is the read noise, and $\sigma_{quant}$ is
the quantization noise. For this work, all the noise terms are in electrons per pixel. Since the shot
noise and the dark noise are modeled as Poisson distributions, and the standard deviation of a
Poisson distribution is the mean of the distribution, $\sigma_{shot}^2$ is equal to the signal, and $\sigma_{dark}^2$ is equal
to the dark current. The read noise is caused by the detector electronics, and will be taken from
a detector specification sheet. The quantization noise comes from the uncertainty of converting
from electrons to digital counts, and the noise of a uniform distribution into bins of width $b$ is
$\sigma_{quant} = b/\sqrt{12}$ [37].

Other sources that are considered noise in the system include stray light photons on the detector,
and the upwelled radiance from path scattering and atmospheric thermal emissions, since these are
not part of the signal from the target. Stray light is a common concern in many remote sensing
systems, and precautions are taken to block stray light paths. A more sophisticated ray tracing
model of the sensor is needed to accurately account for its effects.

2.4 Metrics

After an image is created, either synthetically or from an actual imaging system, we need to de-
termine how well that image captured the information from the scene. In a low-SNR imaging
situation where the imagery is generally panchromatic, we are mostly concerned with the radiometric resolvability and the spatial fidelity of the image. SNR is the primary metric used in this work, as the noise is generally the most limiting factor for radiometric resolvability. The SNR can be calculated for the image as a whole, or each pixel or region on the detector independently. There are many different types of SNR metrics that are used for different purposes [14], and few of them have meaning as a stand-alone value.

A standard metric for rating spatial image interpretability is the National Imagery Interpretability Rating Scale (NIIRS). This is a somewhat subjective rating that requires numerous analysts to “rate” the image on a scale of 0 to 9 based on its perceived interpretability. The General Image-Quality Equation (GIQE) was created to provide a quantitative way to predict the NIIRS value of an image [31]. The GIQE is defined as:

\[
NIIRS = 10.251 - a \log(GSD_{GM}) + b \log(RER_{GM}) - (0.656 \cdot H_{GM}) - \left(0.344 \cdot \frac{G}{SNR_{GIQE}}\right) \tag{2.22}
\]

where \(a = 3.32\) and \(b = 1.559\) if \(RER_{GM} \geq 0.9\), and \(a = 3.16\) and \(b = 2.817\) if \(RER_{GM} < 0.9\). The Ground Sample Distance (GSD) is a measure of scale and resolution, the Relative Edge Response (RER) is a measure of perceived sharpness, \(H\) is a height-overshoot correction, \(G\) is a noise gain term, and \(SNR_{GIQE}\) is relative noise level. \(GSD_{GM}\) is the geometric mean of the GSD in the \(x\) and \(y\) directions on the focal plane, and is defined as:

\[
GSD_{GM} = \left( GSD_x \cdot GSD_y \cdot \sin(\alpha) \right)^{\frac{1}{2}} \tag{2.23}
\]

where \(\alpha\) denotes the angle between \(x\) and \(y\) if the sensor is a scanning array with a non-orthogonal along-track and an across-track dimension. \(GSD_x\) and \(GSD_y\) are defined as:

\[
GSD = \left( \frac{\text{pixel pitch}}{\text{focal length}} \right) \cdot \frac{\text{slant range}}{\cos(\text{look angle})} \tag{2.24}
\]

RER is a measure of the spread along an edge, which is a measure of image sharpness. It is
defined as the difference between two points that are 0.5 pixels on either side of an edge if the edge is normalized from 0 on the low side of the edge to 1 on the high side of the edge. The overshoot height term, $H$, and the noise gain term, $G$, are functions of MTF compensation during post-processing. We are not considering these terms here since no post-processing is done to the generated images.

The $SNR_{GIQE}$ term used in the GIQE equation is defined as the difference in signal between a 15% reflector and 7% reflector, divided by the noise, given by:

$$SNR_{GIQE} = \frac{(S_{\rho=15\%} - S_{\rho=7\%})}{\sigma_{noise}}$$

(2.25)

The GIQE was designed for high-SNR systems (i.e., $SNR_{GIQE} > 2$), so its extension to low-SNR images may not be applicable. The relationship between image interpretability and both GSD and SNR is discussed further with regard to specific sensor parameter trades in Section 5, so the GIQE was briefly described here. Leachtenauer, et al. (1997) has a more thorough explanation and derivation of these equations [31].

Regardless of the specific NIIRS value assigned to an image or the predicted NIIRS value found using the GIQE, the change in NIIRS is related to the change in inverse SNR [14].

It is difficult to find an ideal metric for determining the best low-SNR system parameters because there is so much variation possible in a system or between two systems, and all the parameters effect the image interpretability in different ways. Arguably the best method for determining the interpretability of an image is to use the ratings of human image analysts. This rating can be predicted more accurately through the use of a sensor-specific Image-Quality Equation (IQE). Since the GIQE is designed for higher-SNR images, and no IQE exists for low-SNR systems explicitly, the SNR metric as defined in Eq. (2.25) was used alone for quantitative analysis in this work. A NIIRS-type metric or a low-SNR IQE is needed to perform a full quantitative analysis of the system parameters or comparison between two systems, and is an area for future research.
Chapter 3

Implementation

The process of generating a nighttime image with the new low-SNR sensor includes these independent steps:

1. Set up a valid DIRSIG configuration file.

2. Run a new version of the `make_adb` program.

3. Run an ADB editor program in Matlab to incorporate the new airglow and urban glow sources.

4. Run DIRSIG using the updated ADB file.

5. Run a sensor model program in Matlab.

Steps 1, 2, and 4 are standard steps in generating DIRSIG imagery, and will not be addressed in detail. More information on these steps can be found in the DIRSIG User’s Manual [10].

3.1 Generating an ADB File

The first step of the process is to generate a valid configuration (.CFG) file for use in DIRSIG. The process for doing this is beyond the scope of this work, and is fully covered in the DIRSIG
User’s Manual [10]. This step is where the sources in the scene are specified, including the sun and moon, and any man-made sources in the scene. From here we assume that a valid CFG file has been created with correct scene parameters.

The next step is to run a program called \texttt{make\_adb} that uses the sources specified in the CFG file to generate an ADB file as discussed in Section 2.3.1. The standard \texttt{make\_adb} code first runs MODTRAN with the sensor at the target looking up at the sun and moon if they are above the horizon. MODTRAN outputs the radiance and transmission along the path from the sun to the target and the moon to the target, which are then included in the ADB file. \texttt{make\_adb} then runs MODTRAN again with the MODTRAN sensor at the DIRSIG sensor location looking at the target to get the solar and lunar upwelled radiance, thermal upwelled radiance, and transmission from the target to the sensor. These values are included in the “sensor paths” section of the ADB file. Finally MODTRAN is run with the sensor at the target location looking at the 72 sample path (i.e., all combinations of 6 elevations angles and 12 azimuth angles) to generate the downwelled solar, lunar, and thermal radiances from the atmosphere down to the target.

The \texttt{make\_adb} code also incorporates the spectral background “starlight” file mentioned in Section 2.3.1 into the 72 downwelled terms. The angular distribution of the starlight skydome before this work is shown in Figure 2.19. Since part of this work includes adding a new airglow spectrum to the downwelled radiance, a new spectral background file is used that consists of zero radiance at each wavelength. The new background file along with the commands needed to use it are shown in Appendix A.

To implement the new airglow source, the transmission is needed along the 72 downwelled paths to account for transmission loss from the airglow source in the upper atmosphere to ground. A new version of the \texttt{make\_adb} code was created that is mostly the same as the old version, but instead of only generating 3 columns in the downwelled section of the ADB file (i.e., wavelength, thermal radiance, and solar-scattered radiance) it includes 4 columns for each angle pair: wavelength, thermal radiance, solar-scattered radiance, and transmission from space to ground. Figure 3.1 shows a comparison of the 3-column and 4-column downwelled sections. The use of the new ADB file with 4 columns in the downwelled section instead of 3 columns does not affect any other part
3.2 Matlab ADB Editor

Code was created in Matlab to read, parse, and edit the generated ADB file to add new sources, airglow and urban glow, to the downwelled terms. The Matlab source code is in Appendix B. The code generates a Graphical User Interface (GUI) that allows the user to alter the adjustable model parameters. A image of the GUI as it appears on the screen during run-time is shown in Figure 3.2. The default parameters are shown in the figure. To execute the program, the user clicks the “Run” button at the bottom of the GUI.

The basic adjustable parameters include the input and output ADB file names, which need to be different, and the path name where the files are located. Also included is the skydome mode (i.e., what gets added to the ADB file), and the individual parameters needed as inputs for Garstang’s urban glow model and the airglow model.
The skydome modes determine what radiances are included as $L_d(\theta, \phi, \lambda)$ in the third column of the downwelled section of the output ADB file. The options include:

- **Urban Only** $- L_d(\theta, \phi, \lambda) = L_{d,Garstang}(\theta, \phi, \lambda)$

- **Airglow Only** $- L_d(\theta, \phi, \lambda) = L_{d,airglow}(\theta, \phi, \lambda)$

- **Urban + Airglow** $- L_d(\theta, \phi, \lambda) = L_{d,Garstang}(\theta, \phi, \lambda) + L_{d,airglow}(\theta, \phi, \lambda)$

- **Moon + Urban** $- L_d(\theta, \phi, \lambda) = L_{d,make\_adb}(\theta, \phi, \lambda) + L_{d,Garstang}(\theta, \phi, \lambda)$

- **Moon + Airglow** $- L_d(\theta, \phi, \lambda) = L_{d,make\_adb}(\theta, \phi, \lambda) + L_{d,airglow}(\theta, \phi, \lambda)$

- **Moon + Urban + Airglow** $- L_d(\theta, \phi, \lambda) = L_{d,make\_adb}(\theta, \phi, \lambda) + L_{d,Garstang}(\theta, \phi, \lambda) + L_{d,airglow}(\theta, \phi, \lambda)$

$L_{d,make\_adb}(\theta, \phi, \lambda)$ is the output radiance from the $make\_adb$ program, $L_{d,Garstang}(\theta, \phi, \lambda)$ is the spectral radiance from the urban glow model, and $L_{d,airglow}(\theta, \phi, \lambda)$ is the radiance from the airglow model. The code reads the specific spectral bands from the input ADB file and readjusts the spectra of $L_{d,Garstang}(\theta, \phi, \lambda)$ and $L_{d,airglow}(\theta, \phi, \lambda)$ to match.

The only parameter that can be adjusted for the airglow implementation is a pull-down menu for using the ADB transmission term (i.e., “yes”), which requires an input ADB file with 4 columns.
3.2. MATLAB ADB EDITOR

in the downwelled section, or not using the ADB transmission term (i.e., “no”), in which case the transmission is set to unity for all wavelengths. The rest of the parameters that can be adjusted are for the urban glow model, and include:

- The source spectrum - the spectrum that gets modulated to determine the spectral character of the output. Current options are a low-pressure sodium spectrum or a mercury vapor spectrum. The spectrum is weighted so the illuminance of the spectrum matches the luminance output of the urban glow model (i.e., \( b(\beta, z) \) from Eq. (2.13)).

- The distance from the target to the city center in kilometers

- The elevation of the city above sea level in kilometers

- The elevation of the target scene above sea level in kilometers

- The city radius in kilometers

- The city population

- The azimuthal direction from the scene to the city center in degrees, where 0° is the scene +x direction (usually north).

- The step size of the integration along the path from target into the atmosphere (i.e., \( \overrightarrow{OQ} \) in Figure 2.21). The default is 1 [km].

- The maximum viewing distance from the target through the atmosphere along \( \overrightarrow{OQ} \). The default is 300 [km]. Since the atmosphere is exponentially decaying in density, there is no real upper altitude limit to the scattering layer in the model so it must be specified.

- A percentage of the light from the city that is emitted directly upward. This can change from city to city, and the default is 10%. The light not emitted directly upward is assumed to reflect off a 15% Lambertian reflector on the ground.

- The number of city samples used as the area source. Options are 7 or 21 to match Garstang’s publications. A graph of the intensity and spatial weighting distribution of the samples is
shown in Figure 3.3. Garstang generally uses only 7 samples for distant cities and 21 samples for very close cities or when the target is inside the radius of the city.

The airglow radiance spectrum, \textit{airglow.rad}, the weighted low-pressure sodium radiance spectrum, \textit{sodium.l2r}, and the weighted mercury vapor radiance spectrum, \textit{mercury.l2r}, must also be included in the directory pointed to by the “path” parameter. These files are shown in Appendix C.

3.2.1 Empirical Airglow model

When the “Airglow” option is included in the ADB editor program, an angularly-varying airglow spectrum is added to each of the 72 sample paths in the downwelled section of the ADB file.

The astronomy community has done extensive research into the natural radiances in the night sky, including airglow and diffuse starlight. These spectral radiances are generally subtracted from the images taken at ground-based astronomy sites to yield a “clearer” view of the sky. A database of these measurements was made by the European Organization for Astronomical Research in the Southern Hemisphere (ESO) and can be found at [44]. These measurements are included as the new spectrum of airglow in DIRSIG. They were collected at the Paranal Observatory in northern Chile in 2001 and 2002 using an 8.2 \text{[m]} telescope. The data spans from 0.314 \text{[\mu m]} to 1.043 \text{[\mu m]} and
includes both a broadband “uniform background” emission and narrow-band emission lines. The data has all resolved stars from the skydome removed, but faint, unresolved stars are still included since they cannot be easily removed. Generally, the strong line features in the spectrum are from airglow emissions, and the broadband spectrum is from faint stars. The resolving power of this spectrograph is approximately 45,000 under the configuration used, so the spectral measurement is accurate to .0125 [nm] [20]. It has been corrected for transmission loss through the atmosphere at the time of the collect, so the published radiance represents the radiance seen at zenith in the absence of atmospheric extinction. The measured airglow spectral radiance binned to 10 [nm] increments is shown in Figure 3.4. The resolution of the old “background” spectrum is only 50 [nm] bins. This old ‘natural background’ spectrum in DIRSIG is shown in Figure 3.5.

The angular variation of airglow if viewed from the ground in the absence of atmospheric scattering has been shown to closely match the “van Rhijn function” for most zenith angles [23]. The function, named for Dutch astronomer Pieter Johannes van Rhijn, is given by:
Figure 3.5: Current natural sky background spectrum in DIRSIG [25].
\[ R(h, \phi) = \left( 1 - \left( \frac{a}{a + h} \right) \sin^2(\phi) \right)^{-\frac{1}{2}} \]  

(3.1)

where \( a \) is the radius of the earth, \( h \) is the height of the emitting layer above the earth’s surface, and \( \phi \) is the zenith angle. \( R(h, \phi) = 1 \) at zenith (i.e., when \( \phi = 0 \)). The overall radiance increases closer to the horizon. As discussed in Section 2.2.1.2, airglow in the visible and NIR is primarily emitted by O and OH, with OH being the primary contributor. Nighttime OH emission comes predominately from a band at an altitude of 85 [km], so 85 [km] is used for \( h \) in Eq. (3.1).

The van Rhijn function does not account for transmission loss through the atmosphere, so the angularly varying spectrum is treated as an exo-atmospheric source, and the MODTRAN transmission along each of the 72 sampled downwelled paths is used to account for transmission loss from the emitting layer through the scattering layers to the target. The final radiance for the downwelled airglow at any angle is given by:

\[ L_{d,\text{airglow}}(\theta, \phi, \lambda) = L_{ESO}(\lambda) \cdot R(85, \phi) \cdot \tau(\theta, \phi, \lambda) \]  

(3.2)

where \( L_{ESO}(\lambda) \) is the exo-atmospheric airglow spectrum measured by ESO, shown in Figure 3.4, and read from the file \( \text{airglow.rad} \). \( R(85, \phi) \) is given in Eq. (3.1), and \( \tau(\theta, \phi) \) is the transmission from the target to space along the particular azimuth angle and zenith angle path. If the MODTRAN transmission is selected in the GUI (i.e., “yes” option), \( \tau(\theta, \phi, \lambda) \) is read from the 4th column of the downwelled section of the input ADB file. If the MODTRAN transmission is not selected in the GUI (i.e., the “no” option), \( \tau(\theta, \phi, \lambda) = 1 \) for all \( \theta, \phi, \) and \( \lambda \).

The airglow spectrum shown in Figure 3.4 is modulated to follow the angular structure of Eq. (3.1) for each of the 6 zenith angles. This model includes no azimuthal variation, so all 12 azimuth angles for each zenith angle will have the same spectral radiance values. Although airglow can have additional angular structure, we are concerned only with its contribution to the downwelled radiance. This approach models the overall affect on the downwelled radiance and closely matches the empirical measurements from [23] shown in Figure 2.11. An RGB image of the new airglow-only skydome as seen from an up-looking sensor is shown in Figure 3.6. Like Figure 2.19,
center of the circle is zenith and the outside of the circle is the horizon at any azimuth angle.

For this work, we are only addressing silicon detectors, which are not sensitive to wavelengths much longer than 1 [$\mu$m], so our empirical data is all that is incorporated. As part of a parallel effort, SAMM is being incorporated into DIRSIG as an optional replacement to MODTRAN as a way to include airglow into the upwelled and downwelled radiance calculations. Since airglow at wavelengths shorter than 1 [$\mu$m] is not included in SAMM, a method like the one described here will still be needed.

3.2.2 Garstang’s urban glow model

Garstang’s model is incorporated into DIRSIG by calculating $b(\beta, z)$ from Eq. (2.13) for each azimuth and elevation angle, then incorporating the results into the downwelled radiance in the
3.2. MATLAB ADB EDITOR

ADB file that can be read by DIRSIG.

The most significant limitation to the urban glow model is that it is not spectral in nature. Astronomy is typically done with pan-chromatic imagers that use filters with specific spectral responses, such as the Johnson-Morgan UVB filter system [27]. The $V$ band in this system very closely matches the $V(\lambda)$ response curve of the human visual system. The input to Garstang’s model is a value in lumens, which is by definition spectral flux modulated by the $V(\lambda)$ response curve and integrated over all wavelengths. The output of Garstang’s model is a single value for each direction $(\beta, z)$ which represents the total flux modulated by the $V(\lambda)$ curve and integrated. It does not address urban glow at a finer wavelength resolution. Because the model is not spectral, the direct output of the model will only be meaningful in a DIRSIG simulation if the spectral response of the urban glow model matches the spectral response curve of the DIRSIG sensor.

To account for the non-spectral nature of the output of the urban glow model, a source spectrum (e.g., low-pressure sodium lamp) is used. The spectral radiance of the source is modulated so the total luminance (i.e., total radiance modulated by $V(\lambda)$) matches the output of the urban glow model. In practice this means a spectral radiance with unit luminance is multiplied by the output of the model. The spectral radiance, $L_{d,\text{Garstang}}(\theta, \phi, \lambda)$, input to the ADB file is:

$$L_{d,\text{Garstang}}(\theta, \phi, \lambda) = b(\theta, \phi) \cdot L_{\text{urban}}(\lambda)$$

(3.3)

where $b(\theta, \phi)$ is the output of Garstang’s model from Eq. (2.13), and $L_{\text{urban}}(\lambda)$ is the empirical urban glow spectrum normalized so:

$$L_{\text{urban}}(\lambda) \cdot V(\lambda) = 1 \text{ [lm]}$$

(3.4)

The spectral radiance $L_{\text{urban}}(\lambda)$ can be comprised of a mix of outdoor lighting sources, such as: mercury vapor lamps, high-pressure sodium lamps, low-pressure sodium lamps, and metal halide lamps. For this work, the model includes a low-pressure-sodium-only source and a mercury-vapor-only source. $L_{\text{urban}}(\lambda)$ is read from $\text{sodium.l2r}$ or $\text{mercury.l2r}$, depending on which option is chosen in the GUI. An important note is that the files $\text{sodium.l2r}$ and $\text{mercury.l2r}$ represent inputs to the
model as $L_{urban}(\lambda)$, and are modified versions of the DIRSIG source intensity (.INT) files used for in-scene secondary sources. The units for these new files are wavelength [\mu m] in the first column and an intensity ratio of [(W/sr) / total candelas] in the second column.

There are a few other limitations to the model. First, the atmosphere in the model has uniform mixing and is well behaved, while the actual atmosphere is not. Despite this limitation, this model has been shown to closely match actual radiances observed at numerous telescope sites [16]. Garstang justifies discrepancies between the model and measured data by noting that often atmosphere parameters, such as aerosol content above a distant city, can be drastically different than the aerosol level at the observation site or at the scattering location higher in the atmosphere. The atmosphere in this model has uniform mixing in all dimensions and only varies in density with altitude. Additionally, city ordinances in some cities, such as Tucson, AZ, try to limit light pollution by regulating the direct upward flux from streetlights and the types of sources that may be used. The measured radiances at sites near Tucson tended to have lower values than the model predicts [15][16]. Furthermore, there are multiple approximations to the intensity and location of the city sources. The population and city size used in the model are estimated values. Cities are also usually not circular and do not have uniform illumination. Some locations in cities, like construction sites and sports stadia, tend to have very bright lights, while areas like parks tend to be not as bright. Furthermore, the model includes a finite sampling of the city at a limited number of locations. For some locations inside the city, the skydome may appear to have a stronger downwelled radiance in the direction of a nearby sample point. A more uniform sampling of the city will yield a more accurate skydome. Regardless of these limitations, the model as a whole tends to match empirical data.

A future goal is for DIRSIG to correctly model how the spectrum changes from the source to the target as it is scattered by the atmosphere. In this work, we will treat the spectrum that reaches the target as a scaled version of the spectrum of the source, though this is very likely incorrect. The rationale for using the source spectrum for this work is primarily that the spectrum at the target is unknown and not easily derived. Scattering by aerosols and molecules is spectral in nature, with more scattering at shorter wavelengths than longer wavelengths in the visible spectrum. However,
the transmission through the atmosphere is also spectral, with more transmission in the red than blue visible wavelengths. Since the model is not inherently spectral, and has a variable mix of aerosol and molecular scattering, it cannot accurately predict the spectrum at the target given only the source spectrum. For this reason, a simple modulated source spectrum is used. As a future area of improvement, an empirical measure of the urban glow spectrum will be used in the place of the source-spectra used here.

3.3 Running DIRSIG

After running the Matlab ADB editor code, the updated ADB file contains all the sources mentioned in Section 2.2.1 that were desired in the scene, with the exception of individual secondary sources in the scene. The next step in the process is to run DIRSIG with the updated ADB file. DIRSIG can use the same CFG file as `make_adb` but the ADB file references in the CFG must be changed to the updated ADB file from the Matlab ADB editor. Again a more detailed discussion of the CFG file can be found in [10].

For this work, the spectral response capability of DIRSIG was utilized. Details for using this feature can also be found in [10]. The spectral response file inputs were generated from the literature and represent the QE of different low-SNR detectors discussed in Section 2.2.2. The output of the DIRSIG run is therefore a single-channel pan-chromatic radiance image with the detector QE applied. This greatly simplifies the complexity of the Matlab sensor model and significantly reduces the run-time of both DIRSIG and the sensor model, as it only operates on 2-dimensional images instead of 3-dimensional image cubes.

This approach leads to errors in the sensor model because the optical PSF and quantum conversion from power to photons are spectral processes. The limited case for the system MTF for most low-SNR systems is the detector pixel-pitch, not optical diffraction. This means that small errors in the optical PSF model will not significantly affect the overall system MTF model. The more significant error is in the conversion from power to electrons. For a uniform spectral power, there is 3 times as many photons in the NIR at 900 [nm] as in the blue and UV at 300 [nm]. We
accepted these errors for this initial work as resolving them would greatly increase processing time and the approximations are not unreasonable given the width of our sensor spectral response.

Figure 3.7 shows the spectral QE for different sensor types discussed in Section 2.2.2, including a prototype hybrid sensor built by Teledyne [6] and a full-depletion back-illuminated CCD prototype built by LBNL [30]. These data are used as the spectral response files in DIRSIG. Examples of these spectral response files can be seen in Appendix D. A future goal is to develop a program that will calculate the spectral response function based on the system parameters as discussed in Section 3.4.

### 3.4 Sensor model

Finally, another Matlab code is run that takes the DIRSIG radiance output, applies the optical PSF, the detector parameters to convert from photons to digital counts, and the noise model. The output of this code is an image in digital counts representing what the sensor would see if it was actually operated.

The parameters that are needed to accurately model the sensor were discussed in Section 2.3.4.
They include:

- PSF of the optics.
- F/# and transmission of the optics – or a corresponding G/#
- Detector array size
- Detector pixel pitch
- Pixel fill factor – percentage of the detector that is photo-sensitive
- Integration time
- Dark current – a function of operating temperature and material information
- Readout noise characteristics – Johnson and flicker noise
- Readout technology: CCD vs. CMOS

The image chain approach discussed in Section 2.1 is used for the sensor modeling. The process as modeled for this work is shown schematically in Figure 3.8. The first step is conversion from flux in joules per second to photon flux in photons per second using Eq. (2.20). Next the radiance image output from DIRSIG will pass through the PSF of the optics. The PSF is given by the $SOMB^2$ function from Eq. (2.6). The blurred radiance image is then converted to irradiance on the detector via the G/# in Eq. (2.7). The irradiance at the detector is resampled based on the array dimension, pixel pitch, and pixel fill factor, which is 100% for the low-SNR sensors studied in this work. The irradiance is converted to electrons in each pixel, and noise in electrons is added to the system. Finally the image in electrons is quantized to digital counts. The sensor model code is written in Matlab and can be found in Appendix E.

There are multiple noise terms that must be considered in low-SNR systems. The types of noise included in this model are the dark current, which is dependent on the temperature of the detector, the readout noise, which depends on the sampling rate of the readout electronics, shot noise, which is inherent with any photodetector and a function of the signal level, and quantization
noise. The shot noise is the square root of the signal and is determined for each image. The dark current and read noise are taken from the literature for the LBNL deep-depleted back-illuminated CCD and the Teledyne hybrid sensor [41] [6]. Most low-SNR systems image with very low photons counts, so it is important to count as many electrons as possible. The QSE was set to 1 for all calculations to maximize the resolvability.

3.5 Verification

Verification, as opposed to validation, was done in this work. Validation of the component models was done independently, and this work incorporates them into DIRSIG. Verification includes showing that the components are correctly implemented and that they are correctly interfacing with the DIRSIG scene.
3.5. VERIFICATION

Table 3.1: Comparison of Garstang’s published model results and the results of Matlab ADB edit code.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Elevation (km)</th>
<th>Calculated</th>
<th>Garstang</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K=0.5</td>
<td>K=2</td>
</tr>
<tr>
<td>Tucson</td>
<td>194</td>
<td>1.597</td>
<td>1.817</td>
</tr>
<tr>
<td>Phoenix</td>
<td>176.5</td>
<td>1.662</td>
<td>1.639</td>
</tr>
</tbody>
</table>

Garstang’s Model

Validation of the model has been done independently by Garstang and others in the astronomy community. Verification of Garstang’s model for this project is based on the data from the published papers. The output of his model has been shown to closely match empirical data from various telescope sites. These results can be found in [15] [16] [17] [46]. Verification of the model includes matching $b(\beta, z)$ from Eq. (2.13) to the published luminance values for multiple locations.

Table 3.1 shows the radiance as predicted by Garstang’s implementation of the model vs. the radiance predicted by the implementation done for this project. The units for comparison are luminance in nano-lamberts, [nL], where 1 lambert is equal to $1/\pi$ [cd/cm$^2$]. The values from this implementation are very close to the values published by Garstang in [16]. The differences are due to the inaccuracies in the population estimates, city radius, city distance to the target, and elevations. Garstang simply mentions “1980 populations” without stating the actual values that were used as the input to the model. The 1980 populations, approximate city sizes, elevations, and distances to the target used in this project were all taken from published sources and online tools [9][26][43], and do not necessarily represent the same numbers used by Garstang. The values listed in the table are those used in this implementation.

Garstang mentions that the “cities” used actually represent unified metropolitan areas including the main city and surrounding towns. The population estimates and city radii are functions of the
CHAPTER 3. IMPLEMENTATION

<table>
<thead>
<tr>
<th>Population</th>
<th>TUCSON</th>
<th>City Radius [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10.0%</td>
<td>478,299</td>
<td>11.4</td>
</tr>
<tr>
<td>-7.5%</td>
<td>491,585</td>
<td>11.7</td>
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<tr>
<td>-5.0%</td>
<td>504,871</td>
<td>12.0</td>
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<td>-2.5%</td>
<td>518,157</td>
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<tr>
<td>0.0%</td>
<td>531,443</td>
<td>12.6</td>
</tr>
<tr>
<td>+2.5%</td>
<td>544,729</td>
<td>13.0</td>
</tr>
<tr>
<td>+5.0%</td>
<td>558,015</td>
<td>13.3</td>
</tr>
<tr>
<td>+7.5%</td>
<td>571,301</td>
<td>13.6</td>
</tr>
<tr>
<td>+10.0%</td>
<td>584,587</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Table 3.2: Table of luminance values [nL] from the current urban glow implementation for variations in populations and radii around the 1980 estimates for Tucson.

<table>
<thead>
<tr>
<th>Population</th>
<th>DENVER</th>
<th>City Radius [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10.0%</td>
<td>1,395,891</td>
<td>10.2</td>
</tr>
<tr>
<td>-7.5%</td>
<td>1,434,489</td>
<td>10.5</td>
</tr>
<tr>
<td>-5.0%</td>
<td>1,473,239</td>
<td>10.7</td>
</tr>
<tr>
<td>-2.5%</td>
<td>1,511,999</td>
<td>11.0</td>
</tr>
<tr>
<td>0.0%</td>
<td>1,550,768</td>
<td>11.3</td>
</tr>
<tr>
<td>+2.5%</td>
<td>1,589,537</td>
<td>11.6</td>
</tr>
<tr>
<td>+5.0%</td>
<td>1,628,306</td>
<td>11.9</td>
</tr>
<tr>
<td>+7.5%</td>
<td>1,667,075</td>
<td>12.1</td>
</tr>
<tr>
<td>+10.0%</td>
<td>1,705,845</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Table 3.3: Table of luminance values [nL] from the current urban glow implementation for variations in populations and radii around the 1980 estimates for Denver with K=0.5.

town included in each “city”, but it is unclear which towns are included for any city. Additionally, the city radii were estimated from a map to create a circular approximation for the urban area. Since the parameters used in this project are similarly estimates, small errors exist between the published data and calculated data shown in Table 3.1. Tables 3.2 and 3.3 show how the calculated luminance changes as the population and city radius estimates change. The range of the estimates in the table are +/-10% from the populations and city radii used in Table 3.1, and again the output of the model is in [nL]. It appears that the population and/or radius estimate was too high for Tucson, and too low for Denver. However, both are roughly 5% high or low in the population and radius estimates. With these caveats in mind, and considering the model is intended to be a close approximation and not an exact value, we consider the implementation of the model reasonably verified.
3.5. VERIFICATION

Figure 3.9: Empirical airglow as a function of zenith angle, which closely matched Figure 2.11.

3.5.2 Empirical Airglow Model

Figure 3.9 shows a plot of the ground reaching radiance vs. zenith angle as calculated by the ADB editor code. As expected, the angular dependence of the downwelled radiance matches the measured values shown in Figure 2.11. The angles sampled in Figure 3.9 represent the angles listed in the downwelled section of the ADB file. The sharp drop in radiance seen in zenith angles above 80° in Figure 2.11 is not visible in Figure 3.9 because of the coarse sampling of the ADB file. An image of the new airglow skydome can be seen in Figure 3.6. Again the drop in radiance near the horizon is not visible because the skydome is sampled at 72 locations and the angles between are interpolated. The largest zenith angle sampled is 82.5°, which is close to the location of the maximum value. Since there is no sample location at a larger angle, the intensity falloff due to transmission loss is not seen at the horizon.

Figure 3.10 shows the old DIRSIG background airglow and starlight spectrum on the same chart as the new airglow spectrum, resampled to match the sample spacing of the old spectrum. While the two are not exactly the same, they are reasonably close, especially considering that airglow is highly variable from day-to-day and year-to-year. The old spectrum is taken from published data [34], but it is unclear where or when this spectrum was collected. The new spectrum was collected during
a solar-cycle maximum, so it is expected that the radiance levels would be, if anything, larger, as there are more high energy photons to excite molecules in the upper atmosphere. Additionally, the old spectrum was considered the target-reaching spectral radiance, whereas the new background is considered the exo-atmospheric radiance. The new spectrum would be closer to the old spectrum once it is further attenuated by transmission loss through the atmosphere to the target.

### 3.5.3 Integration of the Skydome into DIRSIG

To ensure the updated `make-adb` function is working, a varying skydome was created, and incorporated into a DIRSIG scene. The test case is a sensor looking down on a scene with a large spherical mirror, which shows the skylight distribution above. The other sources in the scene are absent (i.e., secondary sources off, nighttime with new moon conditions, no thermal emission, and no lunar scattering). The rendered skydome as seen in the mirror should match the skydome from the ADB file.

The sample modified skydome includes urban glow and airglow for a simulated urban image,
which is shown in Figure 3.11. Figure 3.12 shows an image of an urban street at the target location with a spherical mirror at the center of the scene. The mirror shows the skydome above the scene. The city center is located at an angle of 210° counterclockwise from the +x axis in the image (i.e., to the right, which is +y in DIRSIG). The image of the skydome as seen in the mirrored sphere, shows the skydome is correctly implemented.

The skydome seen in Figure 3.11 has a bright spot 180° from where the city center is located (i.e., in the upper right of the figure). While there is likely more back-scatter in this direction than in other directions in the skydome due to the location of the city, this is actually an artifact in the model. Figures 3.13 and 3.14 show the same scenes as Figures 3.11 and 3.12 but with a different sampling of the city in the model. The weight of the sample 180° from the city center is large enough and the sample is close enough to create an artificial increase in the calculated

Figure 3.11: Modified skydome using the Matlab ADB editor. The sample city modeled here has 1,000,000 people, a radius of 6 [km], and is located 1.5 [km] from the target in the +210° direction from the traditional +x axis (i.e., to the right).
Figure 3.12: Image of a scene with a spherical mirror in the center, showing the angular distribution of downwelled sky radiance is at the correct location.
3.5. VERIFICATION

Figure 3.13: Same skydome as Figure 3.11 with a more coarse spatial sampling of the city.

Radiance in that direction. The city sampling used to generate Figure 3.14 contains two strong city samples 30° counterclockwise from the image +x direction (i.e., to the upper right). These strong samples inaccurately increase the radiance seen in that direction. The radiance in any direction is a function of the intensity of the city sample and the distance from the sample to the target location. A better technique for spatially sampling the city lights is needed to more-accurately predict the radiance at points inside the city and is a possible area for future improvement. The effect is somewhat minimized by the smarter sampling of the city in Figure 3.12.
Figure 3.14: Same DIRSIG scene as Figure 3.12 using the skydome from Figure 3.13, which is the more coarse spatial sampling of the city.
Chapter 4

Improvements in DIRSIG imagery

4.1 Improved Aperture-Reaching Radiance Images

To demonstrate the capabilities of the new sources in DIRSIG, a simple scene was constructed that consists of small geometric objects on a flat plane. A framing-array sensor was placed at an altitude of 4 km with a focal length of 200 mm and pixel size of 12 µm. Multiple types of sources were applied to demonstrate the new capabilities.

Before these additions, DIRSIG was only capable of including moonlight and secondary sources in the scene, so some images were not accurately illuminated. In a nighttime scene where there are no external lights, the only source in the DIRSIG scene was moonlight, and the resulting images show clear shadows where no light is visible. This is because moonlight is a strong point source that illuminates from only one direction. Figure 4.1 shows a panchromatic DIRSIG radiance image (i.e., no detector effects applied) of a simple geometric scene with only moonlight illuminating the target. This is what is expected in a rural nighttime scene with no man-made lights nearby.

However if this scene was inside a city, we would expect to see illumination from lights outside the scene, elsewhere in the city, adding radiance to the target. The result of adding urban glow to Figure 4.1 can be seen in Figure 4.2, which includes light from a 1,000,000-person city with a 10
Figure 4.1: A panchromatic DIRSIG image of a simple scene with moonlight only.

Figure 4.2: Simple scene shown in Figure 4.1 illuminated by the moon and urban glow only. This is displayed at the same scale as the moonlight-only figure above.

[km] radius centered 5 [km] away. The figure shows how the scattered light from outside the scene can illuminate the shadows that the moon casts on the back sides of objects.

A similar image is shown in Figure 4.3, but airglow is added instead of urban glow to the downwelled radiance. As would be expected, there is not a significant difference between Figures 4.1 and 4.3. All 3 figures are shown at the same contrast for comparison. Airglow in the visible and NIR simply does not add enough radiance to illuminate the shadows. This is expected since the direct lunar light in the visible spectrum can be 2 orders of magnitude stronger than airglow, as was discussed in Section 2.2.1 and seen in Table 2.1.
4.2 Low-SNR Sensor Model Output

For a low-SNR scene, we are concerned about the limits of the usefulness of a sensor with particular parameters. Section 4.1 discusses how the upgrades to DIRSIG allow it to generate images with various new sources, including images at low illumination levels. There is an illumination limit, though, to what a particular sensor can see from a given scene position. Even with no solar, lunar, urban glow, or airglow sources in the scene, DIRSIG can use the thermal properties of the atmosphere to produce radiance images. An example is seen in Figure 4.6, which is a narrow-band

DIRSIG also has the ability to incorporate secondary sources in the scene. One limitation to using them is that DIRSIG does not account for scattering of the light onto the target. This means that only sources that are very intense or very close to the target supply significant energy. Figure 4.4 shows an RGB DIRSIG scene with secondary sources in the scene and no other sources of illumination (i.e., no moon, urban glow, or airglow). Figure 4.5 is the same RGB scene but with the inclusion of the million-person city mentioned in Section 3.5.3 and shown in Figure 3.11. The lights from the scene are too bright for urban glow to add significant radiance to the target. Similarly moonlight is not bright enough to add radiance to the image if the streetlights are on.

Figure 4.3: Same image as Figure 4.1 with only airglow added to the downwelled radiance. This figure is also shown at the same scale as above.
Figure 4.4: RGB image of a DIRSIG scene where the only illumination is from secondary sources in the scene.

Figure 4.5: RGB image of same scene as Figure 4.4 with the addition of urban glow.
4.2. LOW-SNR SENSOR MODEL OUTPUT

Figure 4.6: DIRSIG scene at 700 [nm] where thermal downwelled radiance is the only source of scene radiance.

image at 700 [nm] of the same winter urban scene as Figure 4.4. This image has no solar, lunar, urban glow, or airglow radiance, but a very small (i.e., $10^{-30}$ [W/cm$^2$·sr·µm]) thermal radiance from the atmosphere is present in the red and NIR. The image is contrast-stretched for display. DIRSIG can use even these very small radiances to generate a simulated image that has discernible spatial content. These radiances, though, are likely too low to be sensed with an actual imager, as they equate to only single photons entering the system, even with very long integration times. Additionally, this ultra-low illumination level is never representative of an actual scene since airglow and background starlight are always present in the skydome.

4.2.1 Improving the Sensor Output

One goal of this work is to determine the illumination conditions at the limit of what can be sensed by a state-of-the-art deep-depleted back-illuminated CCD. The sensor considered here is a prototype sensor designed and built by LBNL. Table 4.1 contains the specific detector parameter range used in this model as published in [41].
There are multiple sensor parameters that can be adjusted to improve the system SNR. They include:

- Larger aperture – collect more photons
- Larger pixels – more signal per pixel, also increases dark current (proportional to pixel area)
- Longer integration time – more signal, also increases dark current
- Lower detector temperature – lowers dark current

While adjusting any of the parameters will improve SNR, some add higher cost to a system than others. Additionally, adjusting some parameters can produce negative image quality effects, and there may be a physical limit to how far the parameter can be adjusted. Sometimes one or more parameters cannot be adjusted at all.

For example, increasing the aperture size is more expensive than increasing the integration time because it requires building larger optics. However, long integration times lead to more image smear for moving platform systems, which most aerial remote sensing systems are. Increasing the pixel size is another way to collect more signal photons per pixel, but it also increases the dark current, and lowers the GSD. As seen in the GIQE from Eq. (2.22), a larger GSD lowers the image quality. Increasing SNR by collecting more signal, on the other hand, will increase the image quality according to the GIQE. The trade to determine the “best” pixel size is between the improved SNR and the increased GSD that comes with increasing the pixel size.

Since there are multiple sources of noise, and only dark noise is temperature dependent, lowering the temperature may not reduce the overall SNR, particularly for a read-noise-limited system. Once

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read Noise</td>
<td>4–6 [electrons]</td>
</tr>
<tr>
<td>Dark Current</td>
<td>$1 \times 10^{-15} \text{ A/cm}^2$ @ $-120^\circ \text{C}$</td>
</tr>
<tr>
<td>Substrate Thickness</td>
<td>300 $\mu\text{m}$</td>
</tr>
<tr>
<td>Resistivity</td>
<td>7000 $\Omega \cdot \text{cm}$</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>$-120^\circ \text{C}$ to $-140^\circ \text{C}$</td>
</tr>
</tbody>
</table>

Table 4.1: Table of values for various parameters of the LBNL deep-depleted back-illuminated CCD [21][41].
4.2. LOW-SNR SENSOR MODEL OUTPUT

the dark noise is no longer the limiting noise contributor, reducing the temperature farther will not affect the overall system performance. All of these factors must be studied to determine the best parameters for a given system.

For the system we are investigating here, we are assuming a framing array sensor on an aerial platform that images from a fixed altitude of 4 [km]. The integration time is limited to 100 [ms] as a nominal value to limit image smear and jitter from platform motion, since we are not fully modeling them here. We assume the system can be cooled from room temperature to roughly $-125\degree [C]$. Ideally we would cool the detector using a thermoelectric cooler, which does not add jitter to the scene. However, a thermoelectric cooler can only cool the system to roughly 100\degree [C] cooler than ambient temperature. The limit for how far a thermoelectric cooler can cool the sensor is a function of the ambient temperature, and is larger at higher ambient temperatures. Figure 4.7 shows an image of the maximum temperature difference between the cold detector and the hotter ambient environment as a function of the ambient temperature [48]. The limit for the aperture size comes from assuming an f/2 system, which does not introduce significant cross-talk in the detector.
4.2.1.1 Changing Integration Time

Figure 4.8 shows the result of changing the integration time of the sensor. This increases both the number of signal photons and the dark current. Since the noise associated with both these sources of electrons is the square-root of the noise source, doubling the integration time will double the signal and double the dark current, while the dark noise and the shot noise increase by a factor of $\sqrt{2}$. All the images shown in the figure are read-noise-limited. The SNR metric from Eq. (2.25) used to compare the images is 0.28 for (a), 0.54 for (b), 1.18 for (c), and 2.01 for (d). The sensor modeled has f/5 optics with a 200 [mm] focal length, flown at 4 [km]. The detector has 12 [$\mu$m] pixels cooled to $-60^\circ$ C. As mentioned in Section 2.4, the absolute SNR does not have a direct meaning in an image quality sense, but increasing SNR will improve image quality. Increasing integration time only effects the SNR term of the GIQE, so the image quality improves with integration time.

4.2.1.2 Changing Pixel Size

Similar to increasing the integration time, increasing the pixel size also increases both the number of photons collected and the dark current. Doubling the area of each pixel doubles the number of photons collected per pixel and also doubles the dark current per pixel. Doubling the dark current increases the dark noise by $\sqrt{2}$, and doubling the photon signal increases the shot noise by $\sqrt{2}$. This improves the SNR and thus the image interpretability. The consequence of increasing the pixel size is that the GSD is larger. From the GIQE, increasing the GSD decreases the overall image interpretability, while increasing the SNR increases the image interpretability. Figure 4.9 shows the output images after Figure 4.2 passes through the sensor model with various pixel sizes. The SNR for each of these images is 0.60 for (a), 1.68 for (b), 2.77 for (c), and 3.83 for (d). Although the SNR in (d) is more than double that of (b), the larger GSD limits the image interpretability. Because the GSD is smaller in (a) and (b) than (d), it is possible to discern the shape of objects in the scene, even though SNR is considerably lower. The sensor modeled in the figure has f/5 optics with integration time of 100 [ms] and the detector cooled to $-60^\circ$ C.
4.2. LOW-SNR SENSOR MODEL OUTPUT

Figure 4.8: Digital count image from Figure 4.1 after passing through the sensor model with integration times of (a) 10 [ms], (b) 20 [ms], (c) 50 [ms] and (d) 100 [ms].
Figure 4.9: Digital count image from Figure 4.1 after passing through the sensor model with pixel sizes of (a) 12 $\mu$m, (b) 24 $\mu$m, (c) 36 $\mu$m and (d) 48 $\mu$m, scaled to the same size on the page.
4.2.1.3 Changing Aperture Size

The SNR can also be improved by increasing the aperture size of the optics. From an SNR standpoint, there is an increase in signal that comes from a larger aperture. A larger aperture focuses more photons onto the detector. Doubling the amount of incoming photons increases the shot noise by $\sqrt{2}$. In terms of overall image quality, there is also an MTF effect that comes from an increased aperture. Since the “blur circle” of the PSF function for a circular aperture from Eq. (2.6) has a radius of $1.22 \frac{\lambda f}{d}$, increasing the diameter of the aperture, $d$, narrows the PSF and leads to a sharper image. To the contrary, however, a small f/# optical system can lead to pixel-cross talk as discussed in Section 2.1.4. The effects of pixel crosstalk are not modeled here, but it is pointed out for discussion. Both these MTF effects change the RER of the image. A increase in the width of the PSF adds more blur to the image and lowers its quality in the GIQE. Figure 4.10 shows the effects of increasing the aperture size for the image from Figure 4.2. For these images, the pixel size is 12 [$\mu$m], the integration time is 100 [ms], and the sensor operates at $-60^\circ\text{C}$. Although it is not an ideal metric for the images, a comparison can be seen between different SNR levels. The SNR for each of these images is 0.51 for (a), 0.86 for (b), 1.71 for (c), and 4.55 for (d).

4.2.1.4 Changing Detector Temperature

Another way to improve the SNR is to reduce the dark noise by cooling the detector. Figure 4.11 shows a graph of the dark current vs. temperature measured for the 250 [$\mu$m]-thick Teledyne HyViSI hybrid sensor [6]. The dark current data published for the LBNL detector are similar to the HyViSI detector at multiple temperatures, but data are not available over the full range of temperatures. Unlike the other methods mentioned above, there is a limit to the SNR improvement, as the dark noise is not the only source of noise in the system. If the system is read- or shot-noise-limited, lowering the dark noise will not significantly affect the system. The transition point where the dark noise is no longer the significant noise source is therefore a function of the other sources of noise. For a low-SNR system, the read noise is usually the other limiting source if dark noise is minimized through cooling.
Figure 4.10: Digital count image from Figure 4.1 after passing through the sensor model with f/# of (a) f/8, (b) f/6, (c) f/4 and (d) f/2.
4.2. LOW-SNR SENSOR MODEL OUTPUT

4.2.1 SNR and system Q

The system Q, given by $Q = \frac{M}{p}$, where $p$ is the pixel pitch, is sometimes used as a design parameter and related to image quality. As discussed in [13], a system that has $Q < 2$ is less influenced by optical aberrations, platform motion, and noise. For low-SNR systems, the ratio of $f/\#$ to pixel pitch is not necessarily related to image quality. The images in Figure 4.9 have $Q$ values of: 0.30 for (a), 0.15 for (b), 0.10 for (c), and 0.08 for (d). Similarly, the values of $Q$ in the images in Figure 4.10 are: 0.30 for (a), 0.23 for (b), 0.17 for (c), and 0.12 for (d). For these images, the value of $Q$ does not necessarily have a direct impact on the image quality because the SNR is so low.

Figure 4.11: Dark current as a function of temperature for the HyViSI hybrid detector [6].

The increase in SNR from decreasing the detector temperature can be seen in Figure 4.12, which is the sensor output of the radiance image from Figure 4.2. The SNR for each of these images is 0.11 for (a), 0.32 for (b), 0.77 for (c), and 1.08 for (d). The system modeled here is $f/5$ optics with a 50 [ms] integration time and 12 [\mu m] pixels.
Figure 4.12: Digital count image from Figure 4.1 after passing through the sensor model with detector at various temperatures (a) $-3^\circ [C]$, (b) $-23^\circ [C]$, (c) $-43^\circ [C]$ and (d) $-63^\circ [C]$. 

(a) SNR = 0.11 
(b) SNR = 0.32 
(c) SNR = 0.77 
(d) SNR = 1.08
Two low-SNR systems with the same value of $Q$ do not produce the same image interpretability. Figure 4.13 shows side-by-side images with the same $Q$ but different aperture diameters and pixel sizes. The SNR for the two images are 1.68 for (a) and 5.30 for (b). This difference in SNR is because the dark noise and shot noise increase when the pixel size increases, but the noise does not increase when the aperture increases. An exception to this is stray light, but that is not considered in the model. It is clear from this figure that $Q$ may not be an important design parameter for low-SNR systems as much as the parameters are individually. In Figure 4.13, the image interpretability is dominated by the larger GSD from increasing the pixel size and the low SNR terms, so the MTF effects of changing $Q$ are not as important. While the value of $Q$ does not necessarily predict image interpretability, particularly for low-SNR systems, it is worth noting that for all the low-SNR trades discussed here, a low $Q$ (i.e., $Q \approx 0.5$ or lower) is desired, and a lower $Q$ improves the SNR.
4.2.3 Illumination limit

It is also desirable to determine what level of illumination is too low to be seen by the sensor. With the sensor adjustable parameters set to their maximum values (i.e., long integration time, large aperture, large pixels, low dark current), objects in the scene illuminated by airglow alone are barely, if at all, detectable. In this test case, the integration time is 100 [ms], the aperture is 0.10 [m] (i.e., f/2 optics), the pixels are 48 [$\mu$m], and the system is read-noise limited at 5 [electrons/pixel] RMS with the temperature at $-123^\circ$ [C], so lowering the dark noise further will not improve the SNR. The simulated radiance image of the scene is given in Figure 4.14(a), and the output image from the sensor model is shown in Figure 4.14(b). The SNR in (b) is 0.87.

This shows that for the state-of-the-art fully-depleted back-illuminated CCD modeled here, airglow represents the limiting case of the illumination level in which objects in the scene can be detected. This demonstrates that other less significant sources do not need to be modeled at this time. Better modeling of starlight, for instance, is not important for these applications because these state-of-the-art sensors cannot distinguish between differences in illumination at that level.
Chapter 5

Sample Low-SNR Sensor Parameter Trade Study

The biggest advantage that the SIG environment and synthetic sensor modeling environment offers is a comparison between overall system designs and system parameters. For example, a simulated back-illuminated CCD and a simulated CCD-CMOS hybrid sensor can be made of the same materials with the same optics and same noise characteristics while looking at the same scene under the same conditions in a SIG environment. A similar study in a real environment would be difficult because of the number of experimental variables. The best way to show the capabilities of the DIRSIG radiance model additions and sensor model is to make an apples-to-apples comparison of different sensor parameters or sensor modalities for a sample scenario.

This study will compare design parameters for the LBNL fully-depleted back-illuminated CCD over a variety of imaging conditions. The DIRSIG imagery used include the scene from Figure 4.1 and the portion of the urban scene used in Figure 4.4. The urban scene is shown in Figure 5.1 under various illumination conditions. Urban glow for this scene is from a 1,000,000-person city with 6 [km] radius centered 1.5 [km] away from the scene. The contrast in each of these images is stretched individually to see the spatial content in the dimmer images. The metric used to evaluate
the system is the GIQE SNR metric from Eq. (2.25). A discussion is also included of how the sensor parameter changes affect the NIIRS estimate based on the GIQE.

Many of the design constraints were discussed in Section 4.2.1. The system in question is a down-looking, framing-array sensor operating from an altitude of 4 [km]. The detector is a deep-depleted back-illuminated silicon CCD with the same QE as the LBNL sensor shown in Figure 3.7. The focal length of the system is fixed at 0.4 [m]. The readout electronics are also fixed, and the read-noise is 5 electrons per pixel. The effects that the variable parameters (i.e., temperature, aperture diameter, pixel size, and integration time) have on the system is dependent on the illumination level in the scene.

A first step is to determine the operating temperature of the detector. Since the read noise is fixed for this system, the dark noise becomes insignificant if it is considerably lower than the read noise. Figure 5.2 shows a graph of the SNR as a function of the detector temperature and the illumination level, which is represented by the DIRSIG run. The 4 illumination conditions shown in Figure 5.1 are shown in Figure 5.2 as DIRSIG runs 1, 2, 4, and 5, respectively. Run 3 is the same combination as run 2 (i.e., airglow and urban glow) with a mercury vapor source instead of a low-pressure sodium source. Run 6 is the same combination as run 5 (i.e., airglow, urban glow, and moonlight) also with a mercury vapor source spectrum. Since the urban glow model calculates the illuminance at the target and not spectral radiance, the overall integrated radiance over the bandpass of the sensor can be different for different source spectra. Low-pressure sodium sources have a lower overall radiance for a given luminance value than mercury-vapor sources. Therefore run 3 and run 6 have a slightly higher integrated radiance than runs 2 and 5, respectively. As seen in the figure, for most nighttime illumination conditions lowering the detector temperature below $-80^\circ$ [C] does not have a significant impact on the image SNR. At that temperature other sources of noise dominate the overall noise term, so lowering the dark noise further will not have any effect on system SNR. The figure shows the model result with an f/5 system and 12 [$\mu$m] pixels. The dark noise is also a function of the size of the pixel, so larger pixels may require more significant cooling to keep the dark noise from dominating the system noise.

The next system parameter to set in the system is the optics. Since the focal length is fixed
Figure 5.1: Radiance images of the urban scene used for the sensor trade study. In order of increasing radiance, (a) is the image illuminated by airglow only, (b) is illuminated by urban glow and airglow only, (c) is illuminated by moonlight and airglow only, (d) is illuminated by moonlight, urban glow, and airglow. These radiance images are contrast-stretched for display purposes.
Figure 5.2: SNR as a function of detector temperature and illumination level. The illumination levels are represented by the DIRSIG run number, and are in increasing order.

at 0.4 [m] for this scenario, the only parameter than can be altered is the aperture size. The advantages of a larger aperture are collecting more photons to improve SNR and decreasing the size of the PSF, which effectively sharpens the image. However there are other limiting factors to consider when designing the optics of the system. The disadvantages to a large aperture are pixel cross-talk from the entrance angle of photons into the substrate, the cost and difficulty of building the larger optics, particularly with regard to wavefront error, and the size and weight constraints for operating the system. Figure 5.3 shows the relationship between the aperture size and SNR. As seen in the figure, increasing the aperture increases the SNR, but the rate at which it improves is a function of the illumination level. (a) represents higher illumination levels, and (b) represents lower illumination. In (a) the system is shot-noise-limited, and in (b) the system is read-noise-limited. The adverse effects of the larger aperture (i.e., pixel cross-talk, additional wavefront error, and build costs) require more detailed system modeling. For this scenario, we chose to use an f/2 system to balance the pros and cons, which in this case is an aperture of 0.2 [m].
Figure 5.3: Relationship between aperture size and SNR for (a) moonlight-only illumination levels, and (b) airglow-only illumination levels.
Next the pixel size of the system needs to be determined. The trade-off for choosing pixel size is improved SNR with larger pixels and increased GSD with larger pixels. Figure 5.4 shows the relationship between pixel size and SNR. SNR increases as the square root of the pixel area in shot-noise-limited or dark-noise-limited systems. Since this system uses square pixels on a framing-array focal plane, the pixel area increases by the square of the pixel pitch. Together this means that SNR increases linearly with pixel pitch, as seen in (a). For lower illumination scenes, like (b), this does not hold true, as the read noise is a significant contributor. The drawback, as seen in Figure 4.9, is that GSD is increased when the pixel size is increased. Figure 5.5 shows the comparison of different pixel sizes on the simulated urban image. For the sample study, we want our imaging system to be able to identify the cars in the scene. Therefore the GSD needs to be small enough to have the targets resolved spatially. For this scenario the pixel size of 24 [$\mu$m] is used, which corresponds to a GSD of 24 [cm] for this system operating at 4 [km]. This maximizes SNR while maintaining a GSD small enough to identify the cars in the scene.

The final parameter that affects SNR is integration time. For most systems, the effective integration time is variable and depends on the illumination conditions. The relationship between integration time and SNR is shown in Figure 5.6. Similar to pixel size, when the system is dark-noise-limited or shot-noise-limited, doubling the integration time increases the SNR by $\sqrt{2}$, as seen in (a). When the read-noise is a significant contributor of system noise, such as in (b), increasing the integration time increases the overall signal without significantly increasing the noise, so SNR appears more linear with integration time.

Some sensor systems allow for multiple pixels to be added together to create a super-pixel, effectively increasing the pixel size of the system. The drawback, as mentioned previously, is that the effective GSD is also decreased with this method. Figure 5.7 shows how the combination of both the pixel size and integration time affect the SNR. Read-noise is a contributing factor in Figure 5.7(b), and not a significant contributor in Figure 5.7(a). For a shot-noise- or dark-noise-limited system as in (a), increasing the pixel pitch or integration time has a smaller affect on SNR than in the read-noise limited case in (b). Making both effective pixel size and effective integration time variable during system operation increases the range of illumination conditions in which the
Figure 5.4: Relationship between pixel size and SNR for (a) moonlight-only illumination levels, and (b) airglow-only illumination levels.
Figure 5.5: Sensor model output for the moonlight scene with pixel sizes of (a) 12 [µm], (b) 24 [µm], (c) 36 [µm], and (d) 48 [µm].
Figure 5.6: SNR as a function of integration time for (a) moonlight-only illumination levels, and (b) airglow-only illumination levels.
sensor can image. As with Figures 5.4 and 5.6, the relationship between SNR and pixel pitch, and SNR and integration time, are dependent on the noise contributions of the system.

Simulated imagery using the parameters outlined above is shown in Figure 5.8 for the radiance images from Figure 5.1. Each image uses f/2 optics at a temperature of $-80^\circ [\text{C}]$. The adjustable sensor parameters (i.e., pixel size and integration time) for (a) are 100 [ms] integration time and 48 [$\mu$m] pixels. Even with a large pixel size and long integration time, noise dominates the scene. Only very low spatial frequencies are visible, such as the road and grass areas. Because road and grass are very uniform in this simulated scene, it is unclear if a real system would produce the same quality image. The sensor for (b) has 50 [ms] integration time and 24 [$\mu$m] pixels. (c) has an integration time of 50 [ms] and 24 [$\mu$m] pixels, and (d) has an integration time of 50 [ms] and 24 [$\mu$m] pixels.

The streetlights in the scene are orders of magnitude brighter than the moonlight or urban glow. Figure 5.9 shows the image with the lights in the scene turned on, with moonlight, urban glow, and airglow all included. Because the streetlights are so bright, the integration time is only 0.1 [ms], with 24 [$\mu$m] pixels and the other parameters remaining the same as for Figure 5.8 (i.e., f/2 optics and cooled to $-80^\circ [\text{C}]$). The shadows from the moonlight, as seen in Figure 5.8(c) and (d).
Figure 5.7: SNR as a function of both pixel pitch and integration time for (a) moonlight-only illumination and (b) airglow-only illumination.
Figure 5.8: Simulated Imagery of the urban scene using the LBNL sensor, f/5 optics and a detector operating at $-80^\circ$ [C]. (a) has only airglow illumination, (b) has urban glow and airglow as sources of illumination, (c) has moonlight and airglow as sources, and (d) has moonlight, urban glow, and airglow.
Figure 5.9: Image of the urban scene with streetlights on using the LBNL detector at $-80^\circ$ [C], with $f/5$ optics, 24 [$\mu$m] pixels, and 0.5 [ms] integration time.
Chapter 6

Incorporating SAMM into DIRSIG

SAMM is a stand-alone code that can replace MODTRAN in DIRSIG to determine downwelled radiance reaching the target, upwelled radiance at the sensor, and transmission rates through the atmosphere. While the inputs and outputs are in a different format than MODTRAN (i.e., no “tape” or “card” structure), all the same information is calculated [8][36]. The addition of SAMM into DIRSIG is not part of this work, but a brief outline for its implementation and the differences between SAMM and MODTRAN will be discussed.

SAMM2, which is being incorporated here and is a combination of MODTRAN-4 and SHARC-4, incorporates SHARC and MODTRAN into a unified code, but does not include all the functionality of MODTRAN. For this reason, the use of SAMM instead of MODTRAN for DIRSIG simulations should be an option set by the DIRSIG user in the CFG file. The capabilities of MODTRAN that are not part of SAMM2 include:

- NOVAM models
- Correlated-k radiative-transfer capability
- Bandpass spectral response functions
- Scaled multiple-scattering contributions
- Separate output for solar irradiance contribution
- Adjustable aerosols and cloud concentrations
- Adjustable ozone and water vapor densities
- Moving cloud locations
- User-defined atmospheric species
- Adjacency-effect modeling

Currently the `make_adb` program generates or reads-in the input “tape” files for MODTRAN based on the CFG file, initiates a run of MODTRAN, and then parses the output file. Implementation of the SAMM code requires modifying the `make_adb` program to generate the input file for SAMM, run SAMM, and parse the output to generate the ADB file. The rest of the process of running DIRSIG after the ADB file is generated remains unchanged.

Like MODTRAN, SAMM calculates the radiance reaching a sensor at a specified location and pointing in a specified direction. The three viewing-geometry options for SAMM include an observer location to specified target location in the atmosphere, observer location to space in a given direction, and observer outside the atmosphere looking through a portion of the atmosphere to space along a “limb view” line-of-site. This line-of-site intersects the atmosphere at a tangent altitude but does not intersect the ground. DIRSIG will need to utilize the observer to specified target location and observer to space options.

The `make_adb` program currently uses the output of multiple MODTRAN runs to determine the upwelled, downwelled, and source radiance and transmission along each path listed in the ADB file. The same runs can be called with SAMM: the observer at the target location on the ground looking to the sun or moon (i.e., source radiance and transmission), the observer at the target location on the ground looking at the 72 different directions in the `make_adb` downwelled section (i.e., downwelled radiance and transmission), and the observer at the sensor location looking at the target location on the ground (i.e., upwelled radiance and transmission).
SAMM can be run in two modes: interactive mode, where the user uses a series of menus to determine the input parameters, or in batch mode, where the input parameters are specified in a SAMM input (.INP) file. Instead of the multiple “tape” files used in MODTRAN, each SAMM uses a single INP file. Each call of SAMM requires a different INP file, but multiple runs can be initiated in a single batch call using a job (.JOBS) file, which is simply a list of the INP files to run. Each INP file listed in the JOBS file needs a unique name, and all output files will have the same unique name with a different file extension.

SAMM has multiple output files, but only 2 files will be needed for DIRSIG. They are a spectral radiance (.SPC) file and a transmission (.TRN) file, both along the viewing path specified in the INP file. The SPC file is a two-column text file with the frequency in wavenumbers \( \text{[cm}^{-1}\text{]} \) in the first column and radiance in \( \text{[W/(cm}^2\cdot \text{sr} \cdot \text{cm}^{-1}\text{)]} \) in the second column. The TRN file is also a two-column text file with wavenumber \( \text{[cm}^{-1}\text{]} \) in the first column and unit-less transmission in the second column. SAMM can only be run using wavenumber spectral bins, so make_adb must convert the spectral bins to wavenumbers if they are specified as wavelengths in the DIRSIG CFG file.

Another output for each SAMM run is the journal file (LOG) contains information generated during the SAMM run. An empty LOG file means that SAMM executed properly without warnings. Fatal errors will terminate the program, but SAMM may run with warnings, which could result in unintended calculations. It is therefore important to check the LOG file for warnings to determine that the SAMM calculations are what was desired.

The overall spectral limits of SAMM are from 1 \( \text{[\mu m]} \) (10,000 \( \text{[cm}^{-1}\text{]} \)) to 40 \( \text{[\mu m]} \) (250 \( \text{[cm}^{-1}\text{]} \)). However, only airglow emission from OH is the modeled at wavelengths shorter than 2 \( \text{[\mu m]} \). All constituents are fully modeled from 2–40 \( \text{[\mu m]} \), while OH is modeled from 1–40 \( \text{[\mu m]} \). The limit to the spectral resolution is 50,000 bands over the bandwidth of the simulation, and the finest spectral resolution possible is 0.001 \( \text{[cm}^{-1}\text{]} \), regardless of the simulation bandwidth.

A sample INP file is shown in Appendix F, specifying the possible inputs to the model. Similar to the MODTRAN tape files, the character spacing for uncommented lines in the files is important. All lines that begin with a capital “C” are comment lines. All distances in the input file are specified
in [km] and all angles in degrees, where 0° is north and +90° is east. Directory names specified in
the INP file must end with a slash “\” or “/” depending on the operating system.

Most of the options for the INP file are explained in the comments section of the file itself, or
in the SAMM2 User's Manual [11]. One of the parameters not discussed in the INP file comments
that is applicable to the DIRSIG implementation is the “path option” on line 28. For the first
parameter on that line, “path type”, a value of 2 is for observer to source, 3 for observer to space,
and 4 is for limb-viewing.

Since SAMM can be run in interactive mode or batch mode, it is possible for the DIRSIG
user to use SAMM in interactive mode to set up a sample INP file with the proper atmospheric
constituents, similar to using a tape-5 editor to set up MODTRAN parameters. The INP file
can then be saved and specified in the DIRSIG CFG file, again similar to the way the tape-5
MODTRAN file is currently specified. The \textit{make\_adb} program will then need to only change the
viewing geometry for each run to generate an ADB file.

\section{Samm Verification}

Since SAMM is essentially MODTRAN with SHARC added, the ADB file and generated imagery
from DIRSIG using SAMM should very similar to the ADB file and generated imagery from
DIRSIG using MODTRAN. This is especially true for bright nighttime scenes where airglow is least
significant. Once implemented, a test can be run to ensure the radiance input to the \textit{make\_adb}
program from SAMM is reasonable and closely matches published radiances at wavelengths longer
than 1 [\mu m].

Samm only models airglow emissions above 30 [km]. A sensor in DIRSIG that is below 30
[km] should have the same transmission terms from sensor to target using either MODTRAN or
Samm. This is a good first test to show that the implementation is correct.

Since airglow emissions are not significant in bright daytime scenes, multiple scene can be
generated in DIRSIG using both MODTRAN and SAMM. The digital count levels should be
nearly equal in the resulting images because the sun and solar scattering dominate.
An image can be created similar to Figure 3.12 of a nighttime scene with no moonlight, scattered moonlight, or urban glow using SAMM. The mirror in the image should show a skydome distribution similar to Figure 3.6.
Chapter 7

Future Work

These are items that are not addressed in this work, but are ideas for future improvements.

• Collect sample urban glow spectra. The urban glow model as it exists now uses source spectra to determine the spectral spread of the energy. It calculates the total radiance reaching the target, but does not determine the spectrum inherently. Since scattering is not uniform spectrally, using the source spectrum as the target-reaching spectrum is not accurate. A series of measurements taken of the night sky of strong urban glow can be used in the model as a more-accurate representation of the spectral character of the radiance on the target.

• Validation of DIRSIG imagery for nighttime scenes. All the models used in this work have been validated independently and incorporated into DIRSIG. They have not been validated after incorporation. An experimental study should be done that collects imagery of a scene that can be rendered in DIRSIG.

• Fully incorporate SAMM into DIRSIG as an alternative option to MODTRAN. SAMM is a more-robust airglow model than the empirical model, but it only models airglow longer than 1 [µm]. Since airglow is most significant between 1 and 2 [µm], it is desirable to study systems in that wavelength region.
• Build scattering directly into DIRSIG. Ideally scattering from secondary sources could be incorporated into DIRSIG directly so the same atmospheric parameters can be used for all cases. Currently DIRSIG relies on calls to MODTRAN to find the radiance and transmission along various paths. There are significant limitations to this approach, most notably that scattering from sources other than the sun and moon cannot be included. Garstang’s model offers a way to incorporate scattering from secondary sources, but as discussed in Section 3.5.1, there are limitations to this method.

• Upgrade the sensor model to accurately calculate the spectral response function (QE) based on the sensor parameters.

• Study the effects of noise on the system to determine if low-SNR systems can truly be modeled with Gaussian statistics.

• Explore different metrics for low-SNR systems, including how the changing SNR affects the NIIRS rating for low-SNR imagery, and if NIIRS is still an applicable metric. It is important to determine if there is a minimum SNR level for which the GIQE is applicable, and what SNR metrics best relate to image interpretability.

• Conduct sensor trade studies for other sensor types discussed in Section 2.2.2.


Bibliography


Appendix A

New Spectral Background File

The following is the new background file, zeros.dat, used by the make_adb program for this work. The first column is the wavelength in [$\mu$m], and the second column is the background radiance reaching the ground in [W/(cm$^2$·sr·$\mu$m)].

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Radiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.40</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.45</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.50</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.55</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.60</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.65</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.70</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.75</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.80</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.85</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.90</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>0.95</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.00</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.05</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.10</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.15</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.20</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.25</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.30</td>
<td>0.000000e1</td>
</tr>
<tr>
<td>1.35</td>
<td>0.000000e1</td>
</tr>
</tbody>
</table>

This background file is incorporated through the make_adb “use_config” option when called from the command line. The Unix command to execute the routine is:

```
>> ./make_adb -use_config myconfig.txt run.cfg
```

where run.cfg is the CFG file for the DIRSIG run, and myconfig.txt is a text file that includes the new background file. The following is the text file myconfig.txt:
MAKE_ADB_CFG = 1.0
MODTRAN {
    MODTRAN_EXE = /dirs/pkg/Mod4v3r1/Mod4v3r1.exe
    MODTRAN_DATA_DIR = /dirs/pkg/Mod4v3r1/DATA
    MODTRAN_MIN_DELTA = 1.0
}
BACKGROUND_RADIANCE_FILE = ./zeros.dat
Appendix B

ADB Editor Matlab Code

This is the Matlab code that is referenced in Section 3.2:

```matlab
% Tony Risuto
% ADB Editor code that includes Garstang’s urban glow model and empirical
% airglow model into BIRISG
%
% 17 Jan 09
% UPDATED 04May09

function GarstangGUI

clear;
close all;
close all;

choose the appropriate spectral source file
pathName = 'C:\Documents and Settings\Administrator\My Documents\MATLAB';

inFile = 'inFile.adb';
outFile = 'outFile.adb';

%Variables:
%options are 'sodium' (default) and 'mercury'
sourceType = 'sodium';
%options are 'add' (default) and 'replace'
skyType = 'Moon + Urban + Airglow';
```
APPENDIX B. ADB EDITOR MATLAB CODE

% Variables set by the user, initial [default] variables
X = 1.0;  % aerosol level
Adv = 0.5;  % target elevation
city = 21;  % city samples
numCities = 1;  % cities
R = 11;  % city radii
P = 100000;  % city populations
H = 0.95;  % city elevations
D = 5;  % city distances to target
cTheta = 10;  % azimuth from target to city, counter-clockwise from positive y
F = 1.1;  % percent of light directly emitted upward
step = 1;
max = 200;
alpha = 1;

% Pseudo Variables [can change, but likely won’t, hard coded]
L = 1000;  % # luminos per person in the city (5000 for users 1000)
G = 0.15;  % very collectivity of the earth surface
nSamples = 12;  % # aerosol samples
sSamples = 6;  % # elevation samples

% Constants:
M0 = 0.52519*1E15;  % molecular scattering coeff [cm^-1]
sigmaM = 4.63*1E10;  % Rayleigh scattering cross-section [cm^-2]
sigmaR = 0.12;  % molecular scale height [km^-1]
sigmaG = 0.657 + 0.659 * R;  % aerosol scale height [km^-1]
K = 6.77;  % earth radius in km
A = 85;
option = 16/9/0/0;
figure = 45;
B = input([nSamples, sSamples]);
L0 = input([nSamples, sSamples]);

xStep = zeros(1, nSamples);
yStep = zeros(1, nSamples, 1);

% Initialize the GUI
% Create and then hide the GUI as it is being constructed.
F = figure('Visible','off','Position',[300,300,500,315]);

% Pack info
hText = uicontrol('Style','pushbutton','String','Change Path','...'
  'Position',[20,200,80,25],...
  'Callback',(@selectFileCallback));
hPack = uicontrol('Style','text','String','Pack ',...''
  'Position',[220,200,40,25]);
hPackText = uicontrol('Style','text','String','packName',...
  'Position',[350,250,540,25]);

% Input ABD file
hInFileText = uicontrol('Style','text','String','Input ABD File = ',...
  'Position',[30,250,90,25]);
hInFile = uicontrol('Style','edit','String',inFile, '...
  'Position',[310,250,100,25], 'Callback',(@inFileCallback));

% Output ABD file
hOutFileText = uicontrol('Style','text','String','Output ABD File = ',...
  'Position',[30,320,90,25]);
hOutFile = uicontrol('Style','edit','String',outFile, '...
  'Position',[310,320,100,25], 'Callback',(@outFileCallback));

% Source spectrum
hSourceText = uicontrol('Style','text','String','Source Spectrum = ',...
  'Position',[30,50,100,25]);
hSource = uicontrol('Style','popmenu', '...
  'String',{'Sodium', 'Mercury'},
  'Position',[330,50,130,25],...
APPENDIX B. ADB EDITOR MATLAB CODE

%% City distance info.

% Set distance text

set(button,'String','City distance (km) = ',
    'Position',[200,80,140,25]);

% Set distance menu

set(menu,'String',num2str(D1),
    'Position',[300,80,30,25],
    'Callback', [@DistanceMenuCallback]);

% Set light emitted upward

set(button,'String',num2str(f1),
    'Position',[220,50,140,25]);

% Set run the code button

set(button,'String','Run',
    'Position',[20,20,40,25],
    'Callback', [@RunCallback]);

\\

% Initialize the GUI.

% Assign the GUI a name to appear in the window title.

set(f,'Name','EarthSky Model Setup');

% Move the GUI to the center of the screen.

movegui(f,'center');

% Make the GUI visible.

set(f,'Visible','on');

\\

% GUI Callbacks

\\

function sourceNameCallback(source,eventdata)

% Determine the selected data set.

str = get(source, 'String');

val = get(source, 'Value');

\\

function skyNameCallback(source,eventdata)

% Determine the selected data set.

str = get(source, 'String');

val = get(source, 'Value');

% Set current data to the selected data set.

switch str(val);
    case 'Mercury'
        sourceType = 'Mercury';
    case 'Venus'
        sourceType = 'Venus';
    case 'Earth'
        sourceType = 'Earth';
    case 'Moon + Urban + Airglow'
        sourceType = 'Moon + Urban + Airglow';
    case 'Moon + Urban + Airglow'
        sourceType = 'Moon + Urban + Airglow';
    case 'Moon + Urban + Airglow'
        sourceType = 'Moon + Urban + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
    case 'Moon + Airglow'
        sourceType = 'Moon + Airglow';
end

end

end
function setFileCallback(source, eventdata)
    % Choose the correct data path for input files
    pathName = uigetdir;
    hPathText = uicontrol('Style', 'text', 'String', pathName, ...'
    'Position', [140, 200, 300, 20]);
end

function inFileMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    inFile=str;
end

function outFileMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    outFile=str;
end

function XMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    xStr=strdouble(str);
end

function YMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp=strdouble(str);
    XStr = temp;
end

function TMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    val = get(source, 'Value');
    % Set current data to the selected data set.
    switch str(val);
    case 'Yes'
        uaaD8=1;
    case 'No'
        uaaD8=0;
end
end

function citySampleMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    val = get(source, 'Value');
    % Set current data to the selected data set.
    switch str(val);
    case '7'
        CSample=7;
    case '23'
        Csample=21;
    case '42'
        Csample=42;
end
end
function moveMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    uMax = temp;
end

function integrStepMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    uStep = temp;
end

function radiusMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    R = temp;
end

function popMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    P = temp;
end

function elevMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    H = temp;
end

function directMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    CTheta = temp;
end

function distanceMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    D = temp;
end

function exitUpMenuCallback(source, eventdata)
    % Determine the selected data set.
    str = get(source, 'String');
    temp = str2double(str);
    F = temp;
end
function returnCallback(source, eventdata)
    close all;
    Geotrans;
end

% ********************************* start of the code section

Function Geotrans

input = [pathName 'inFile'];
output = [pathName 'outFile'];
singleFile = [pathName 'single.rst'];
switch sourceType
    case 'mercury'
        sourceFile = [pathName 'mercury.lit'];
    otherwise
        sourceFile = [pathName 'sodium.lit'];
end
h = M11;
d = Adiff-h;
totalWavelength=0;

% read in the ADR file to find the output bands
% write to the new ADR file as you go...
% start by reading/writing the header info until we get to the line we want
fid = fopen(input, 'r');
outFile = fopen(output, 'w');
time = '';

while strcmp(line, '')
    time = fgets(fid);
    fprintf(outFile, '%s
', time);
end

% read in the min wavelength
time = fgets(fid);
line = time[10:45];
minWave = str2num(line);
fprintf(outFile, '%s
', line);

% read in the max wavelength
time = fgets(fid);
line = time[10:45];
maxWave = str2num(line);
fprintf(outFile, '%s
', line);

% read in the space between wavelengths
time = fgets(fid);
line = time[10:45];
deltaWave = str2num(line);
fprintf(outFile, '%s
', line);

% calculate the correct number of output bands
numBands = ((maxWave - minWave)/ deltaWave)+1;

% read in the source file into an array
sourceFid = fopen(sourceFile);
time = fgets(sourceFid);
APPENDIX B. ADB EDITOR MATLAB CODE

```matlab
while tline=-1
    bandCount=bandCount+1;
    line = str2num(tline);
    centerFull (bandCount) = line(1);
    spectrumFull(bandCount) = line(2);
    tline = zep1(sourceFid);
end

% re-bin spectrum to the correct number of output bands (assumes uniform response across the band)
centerSource = (zeros(numBands+1,1));
spectrumSource = (zeros(numBands+1,1));
for n=numBands+1
    centerSource(n) = minWave+(n-1)*deltaWave;
end
for m=1:bandCount
    if (centerFull(m)>=centerSource(m)-(deltaWave/2)) & (centerFull(m)<=centerSource(m)+(deltaWave/2))
        spectrumSource(m) = spectrumSource(m)+spectrumFull(m);
    end
end
end

% read in airglow spectral data
bandCount = 0;
airglowFid = fopen('airglowFile');
tline = zep1(airglowFid);
while tline>=-1
    bandCount=bandCount+1;
    line = str2num(tline);
    centerAir (bandCount) = line(1);
    spectrumAir (bandCount) = line(2);
    tline = zep1(airglowFid);
end

% re-bin spectrum to the correct number of output bands (assumes uniform response across the band)
centerAirglow = (zeros(numBands+1,1));
spectrumAirglow = (zeros(numBands+1,1));
for n=numBands+1
    centerAirglow(n) = minWave+(n-1)*deltaWave;
end
for m=1:bandCount
    if (centerAir(m)>=centerAirglow(m)-(deltaWave/2)) & (centerAir(m)<=centerAirglow(m)+(deltaWave/2))
        spectrumAirglow(m) = spectrumAirglow(m)+spectrumAir(m);
    end
end

% calculate luminance from Oerstang's model
for n=1:length(city)
    chi = (pi/2)*center(city);
    chi = (pi/2)*center(city);
    if (cos(chi))>=0 & (sin(chi))>=0
        \( L = \frac{|\mathbf{v}|}{|\mathbf{v}'|} \)
    else
        \( L = 0 \)
    end
    for zenith=0:2*xr
        for azimuth=0:2*yr
            \end{verbatim}

```
\[ \text{vonRhJal} = \text{atan}(1 - ((1 + 2) - 2 \cdot \text{sin}(\theta) - 2)) \]

if \( \text{W3D} \) if city is below the plane, we need to integrate from the city plane to infinity
\[ \text{W3D} = ((1 + 2) \cdot \text{sin}(\theta) - 2) = \text{atan}(\text{sin}(\theta)) \]

\[ \text{weight} = \text{atan}(\text{sin}(\theta)) \]

\[ \text{weight} = \text{atan}(\text{sin}(\theta)) + \text{atan}(\text{cos}(\theta)) \]

\[ \text{weight} = (\text{sin}(\theta) + \text{cos}(\theta)) \]

\[ \text{weight} = \text{atan}(\text{sin}(\theta)) + \text{atan}(\text{cos}(\theta)) \]

\[ \text{weight} = 0 \]

\[ \text{if} \]

\[ \text{weight} = 0 \]

\[ \text{for} \]

\[ \text{count} = 1 ; \text{count} = \text{count} + 1 \]

\[ \text{switch} \]

\[ \text{case} \]

\[ \text{if} \]

\[ \text{case} \]

\[ \text{X} = 0; \text{Y} = 0; \text{weight} = 1/4 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(2/3) \cdot \text{R}(n); \text{Y} = 0; \text{weight} = 1/8 \]

\[ \text{case} \]

\[ \text{X} = -\text{sqrt}(2/3) \cdot \text{R}(n); \text{Y} = 0; \text{weight} = 1/8 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(1/6) \cdot \text{R}(n); \text{Y} = \text{R(n)/2} \cdot \text{sqrt}(2); \text{weight} = 1/8 \]

\[ \text{case} \]

\[ \text{X} = -\text{sqrt}(1/6) \cdot \text{R}(n); \text{Y} = -\text{R(n)/2} \cdot \text{sqrt}(2); \text{weight} = 1/8 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(1/6) \cdot \text{R}(n); \text{Y} = \text{R(n)/2} \cdot \text{sqrt}(2); \text{weight} = 1/8 \]

\[ \text{case} \]

\[ \text{X} = -\text{sqrt}(1/6) \cdot \text{R}(n); \text{Y} = -\text{R(n)/2} \cdot \text{sqrt}(2); \text{weight} = 1/8 \]

\[ \text{end} \]

\[ \text{elseif} \ (\text{count} = 2) \]

\[ \text{switch} \]

\[ \text{case} \]

\[ \text{X} = 0; \text{Y} = 0; \text{weight} = 1/8 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 10) \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 10) \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 2) \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 2) \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 3) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 3) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 4) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 4) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 5) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 5) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 6) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 6) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 7) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 7) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 8) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 8) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]

\[ \text{case} \]

\[ \text{X} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{cos}(2 \cdot \pi / 9) \cdot 10 \cdot \text{R}(n); \text{Y} = \text{sqrt}(6 - \text{sqrt}(6)) \cdot 10 \cdot \text{sin}(2 \cdot \pi / 9) \cdot 10 \cdot \text{R}(n); \text{weight} = 10 \cdot \text{sqrt}(6) / 380 \]
APPENDIX B. ADB EDITOR MATLAB CODE

```matlab
    case 11
    x = sqrt((6-sqrt(6))/10) * cos(2*pi*10/10) * R(n); y = sqrt((6-sqrt(6))/10) * sin(2*pi*10/10) * R(n);
    weight = (6-sqrt(6))/360;
    case 12
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*11/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*11/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 13
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*12/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*12/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 14
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*13/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*13/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 15
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*14/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*14/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 16
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*15/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*15/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 17
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*16/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*16/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 18
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*17/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*17/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 19
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*18/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*18/10) * R(n);
    weight = (6+sqrt(6))/360;
    case 20
    x = sqrt((6+sqrt(6))/10) * cos(2*pi*19/10) * R(n); y = sqrt((6+sqrt(6))/10) * sin(2*pi*19/10) * R(n);
    weight = (6+sqrt(6))/360;

    end

    geometric equations:
    L = sqrt((x^2)+(y^2)+(x=R(n))+(y*sin(chi/2)^2)+(y^2)+(x=R(n))^2)+(y=sin(2*pi*10/10)*R(n))^2);
    \% linear distance from city to target
    theta = acos(((x=R(n))+(y*sin(2*pi*10/10)*R(n)))/(cos(2*pi*10/10)*R(n)+sin(2*pi*10/10)*R(n)));
    \% x^2=(cos(chi)^2+sin(chi) cos(beta)+cos(chi) cos(a))... + x^2=sin(chi) cos(beta)-sin(chi) cos(a)...
    \% y^2=(sin(chi)^2+sin(beta)-x=R(n)+A)*cos(a)).../1;
    \% elevation angle from city plane to scattering direction

    uTot = 0;
    for u = uTot:uTot+StepMax \%for every discrete volume along the path
```
\[
\begin{align*}
a &= \sqrt{(u^2) + (v^2) - (2u v \cos(\theta_{\text{inc}}))} \quad \text{// distance from city to scattering volume} \\
\phi &= \arccos\left(\frac{(u^2) + (v^2) - (w^2)}{2u v}\right) \quad \text{// angle at the city between the line to the} \\
&\quad \text{target and the line to the scattering volume} \\
d_{\Delta} &= ((u^2) + (v^2) + (w^2))^{1/2} \quad \text{// target distance} \\
\theta &= \arccos\left(\frac{(u^2) + (v^2) - (w^2)}{2u v}\right) \quad \text{// angle at the scattering volume} \\
\phi_{\text{inc}} &= \arccos\left(\frac{(u^2) + (v^2) - (w^2)}{2u v}\right) \quad \text{// angle at the city} \\
h &= (E + M) \times \left(\frac{1}{2}\right) - 1 \quad \text{// elevation of the scattering volume}
\end{align*}
\]

\text{/* radiametric equations*/}
\text{Tup} = (L (\Phi/10)[2\pi \Phi] + (\pi/2 - (\Phi/10)) \cos(\psi_{\text{inc}}) + 0.555 \times f(\psi_{\text{inc}}))/41
\text{// light emitted up from the city}

\text{if (s <= s$_{\text{lt}}$/3) }
\begin{align*}
p &= \exp(-a \times \exp(-b \times \exp(-c \times \exp(-d \times \exp(-e \times \exp(-f \times \exp(-g \times \exp(-h \times \exp(-i \times \exp(-j \times \exp(-k \times \exp(-l \times \exp(-m \times \exp(-n \times \exp(-o \times \exp(-p \times \exp(-q \times \exp(-r \times \exp(-s \times \exp(-t \times \exp(-u \times \exp(-v \times \exp(-w \times \exp(-x \times \exp(-y \times \exp(-z \times \exp(-\theta_{\text{inc}} - \Phi/100))/10)))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10))/10)/\]
APPENDIX B. ADB EDITOR MATLAB CODE

```matlab
b(azimuth, zenith) = pi*H*sigmaG*exp(-c*R(h))*sy/3*1/100; % Lambertian.  tr = {pi}/candela/cm^2
LUM(azimuth, zenith) = b(azimuth, zenith)*pi;  % candela/cm^2 = lumens/(cm^2 sr)
V(azimuth, zenith) = (20.7222*(log10(b(azimuth, zenith)*1/100) + 24.09))/0.02109;

end
end

% I/O with the input and output ADB files
line = '';
while strcmp(line,'$CONVEX_PATHS { }==0;
line = fgets(fid);
fprintf(outfile, '%s', line);
end

total = zeros(numBands,1,);  % for zenith=80xSamples
2 = (20*log10(thi)/100, for azimuth=8xSamples

while strcmp(line, 'SPECTRAL_DATA { }==0;
line = fgets(fid);
fprintf(outfile, '%s', line);
end

for band = 1:numBands
  t = fscanf(fid, ' %f %f %f %f', 4);
  teff = tband(zenith)^4(4);
  if (teff>=2)
    t = tband(fid, ' %f %f %f %f', 4);
    intFactor = vband(zenith)^4(4);
    if (teff>=2)
      t = tband(zenith)^4(4);
    elseif (teff>=2)
      intFactor = vband(zenith)^4(4);
      \ needs a hard-coded transmission term
  end
  line = fgets(fid);
  switch skycmd
    case 'Urban + Airglow'
      t3 = (LUM(azimuth, zenith)*spectrumband(band)+spectrumAirglow(band)^4(intFactor));
    case 'Urban Only'
      t3 = (LUM(azimuth, zenith)*spectrumband(band));
    case 'Airglow Only'
      t3 = spectrumAirglow(band)^4(intFactor);
    case 'Moon + Airglow'
      t3 = t3^4(spectrumAirglow(band)^4(intFactor));
    case 'Moon + Urban'
      t3 = t3^4(LUM(azimuth, zenith)^4(intFactor));
    end
  fprintf(outfile, '  %f %f %f %f
', t(1), t(2), t,)
end
end

% replaces the "total" downwelled section of the ADB file
while strcmp(line,'SPECTRAL_DATA { }==0;
line = fgets(fid);
fprintf(outfile, '%s', line);
end
```

for band = 1:lenbands
    t = fscanf(fid, '%f %e %e', 3);
    time = fscanf(fid);
    fprintf(outfile, ' %7.6f %5.4e %5.4e\n', t(1), t(1), (total@band)/2/phi);
end

cline = fscanf(fid);
while cline
    fprintf(outfile, '%d\n', cline);
    time = fscanf(fid);
end
fclose('all');
end
Appendix C

Source Spectra for the ADB Editor Program

C.1  *airglow.rad*

The following spectral radiance text file is called *airglow.rad*. The first column is the wavelength in $[\mu m]$, and the second column is the radiance leaving the emitting layer from zenith in $[W/(cm^2\cdot sr\cdot \mu m)]$.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Radiance (W/(cm²·sr·µm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.310000</td>
<td>7.21888E-12</td>
</tr>
<tr>
<td>0.320000</td>
<td>8.11596E-12</td>
</tr>
<tr>
<td>0.330000</td>
<td>7.79965E-12</td>
</tr>
<tr>
<td>0.340000</td>
<td>7.83582E-12</td>
</tr>
<tr>
<td>0.350000</td>
<td>7.44533E-12</td>
</tr>
<tr>
<td>0.360000</td>
<td>7.14828E-12</td>
</tr>
<tr>
<td>0.370000</td>
<td>7.91788E-12</td>
</tr>
<tr>
<td>0.380000</td>
<td>7.35084E-12</td>
</tr>
<tr>
<td>0.390000</td>
<td>7.57116E-12</td>
</tr>
<tr>
<td>0.400000</td>
<td>7.64313E-12</td>
</tr>
<tr>
<td>0.410000</td>
<td>7.45394E-12</td>
</tr>
<tr>
<td>0.420000</td>
<td>6.70738E-12</td>
</tr>
<tr>
<td>0.430000</td>
<td>6.61795E-12</td>
</tr>
<tr>
<td>0.440000</td>
<td>6.88076E-12</td>
</tr>
<tr>
<td>0.450000</td>
<td>6.77725E-12</td>
</tr>
<tr>
<td>0.460000</td>
<td>6.61035E-12</td>
</tr>
<tr>
<td>0.470000</td>
<td>6.4051E-12</td>
</tr>
<tr>
<td>0.480000</td>
<td>6.59305E-12</td>
</tr>
<tr>
<td>0.490000</td>
<td>6.53699E-12</td>
</tr>
<tr>
<td>0.500000</td>
<td>6.4029E-12</td>
</tr>
<tr>
<td>0.510000</td>
<td>6.67619E-12</td>
</tr>
<tr>
<td>0.520000</td>
<td>6.8374E-12</td>
</tr>
</tbody>
</table>
### APPENDIX C. SOURCE SPECTRA FOR THE ADB EDITOR PROGRAM

<table>
<thead>
<tr>
<th>Wavelength [µm]</th>
<th>Intensity Conversion Factor [(W/sr) / (cd·µm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.530000</td>
<td>6.58765E-12</td>
</tr>
<tr>
<td>0.540000</td>
<td>6.38178E-12</td>
</tr>
<tr>
<td>0.550000</td>
<td>1.49299E-11</td>
</tr>
<tr>
<td>0.560000</td>
<td>6.47393E-12</td>
</tr>
<tr>
<td>0.570000</td>
<td>6.38178E-12</td>
</tr>
<tr>
<td>0.580000</td>
<td>8.39995E-12</td>
</tr>
<tr>
<td>0.590000</td>
<td>7.6183E-12</td>
</tr>
<tr>
<td>0.600000</td>
<td>6.53263E-12</td>
</tr>
<tr>
<td>0.610000</td>
<td>6.6858E-12</td>
</tr>
<tr>
<td>0.620000</td>
<td>7.9666E-12</td>
</tr>
<tr>
<td>0.630000</td>
<td>1.90614E-11</td>
</tr>
<tr>
<td>0.640000</td>
<td>7.28972E-12</td>
</tr>
<tr>
<td>0.650000</td>
<td>7.8332E-12</td>
</tr>
<tr>
<td>0.660000</td>
<td>6.70551E-12</td>
</tr>
<tr>
<td>0.670000</td>
<td>6.945E-12</td>
</tr>
<tr>
<td>0.680000</td>
<td>8.6253E-12</td>
</tr>
<tr>
<td>0.690000</td>
<td>8.5463E-12</td>
</tr>
<tr>
<td>0.700000</td>
<td>7.3347E-12</td>
</tr>
<tr>
<td>0.710000</td>
<td>7.1489E-12</td>
</tr>
<tr>
<td>0.720000</td>
<td>1.1517E-11</td>
</tr>
<tr>
<td>0.730000</td>
<td>1.2361E-11</td>
</tr>
<tr>
<td>0.740000</td>
<td>9.1903E-12</td>
</tr>
<tr>
<td>0.750000</td>
<td>9.0543E-12</td>
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### C.2 sodium.l2r

The following is a portion of a text file, *sodium.l2r*, that lists the spectral radiant intensity for 1 lumen of a low-pressure sodium source. The first column is the wavelength in [µm], and the second column is the intensity conversion factor [(W/sr) / (cd·µm)]. The complete text file spans the wavelength range from 0.4–2.5 [µm].
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C.3  mercury.l2r

The following is a portion of a text file, mercury.l2r, that lists the spectral radiant intensity for 1 lumen of a mercury vapor source. The first column is the wavelength in [µm], and the second column is the intensity conversion factor [(W/sr) / (cd·µm)]. The complete text file spans the wavelength range from 0.4–2.5 [µm].

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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
<td>0.570000</td>
<td>2.06422E-06</td>
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</table>
Appendix D

Sample DIRSIG Spectral Response Files

The QE curves are taken from the literature and input into DIRSIG to generate pan-chromatic radiance images. The first file is the DIRSIG spectral response file for a typical front-illuminated CCD sensor: `FrontIllumCCD.rsp`.

```plaintext
DIRSIG_RSP
#
# NAME: Standard Front Illuminated CCD
# PURPOSE: Spectral response function for standard front-illuminated CCD
# BAND {
    NAME = front illuminated sensor
    MINIMUM_WAVELENGTH = 0.300
    MAXIMUM_WAVELENGTH = 1.000
    DELTA_WAVELENGTH = 0.020
}

TYPE = INTEGRATED
RESPONSE {
    0.30 0.0066
    0.32 0.0066
    0.34 0.0066
    0.36 0.0099
    0.38 0.0131
    0.40 0.0197
    0.42 0.0255
    0.44 0.0721
    0.46 0.1115
    0.48 0.1475
    0.50 0.2262
    0.52 0.2286
```

### APPENDIX D. SAMPLE DIRSIG SPECTRAL RESPONSE FILES

The second file is the DIRSIG spectral response file for the LBNL sensor modeled in this project:

```plaintext
LBNL.rsp
```

```plaintext
dirsig_rsp
#
# NAME: Lawrence Berkeley National Lab NIR detector
# PURPOSE: Spectral response function for back-illuminated NIR detector
# BAND {
  NAME = LBNL sensor
  MINIMUM_WAVELENGTH = 0.300
  MAXIMUM_WAVELENGTH = 1.080
  DELTA_WAVELENGTH = 0.020
}

  TYPE = INTEGRATED
  RESPONSE {
    0.30 0.2033
    0.32 0.3410
    0.34 0.4295
    0.36 0.5311
    0.38 0.6230
    0.40 0.7180
    0.42 0.7934
    0.44 0.8098
    0.46 0.8033
    0.48 0.7967
    0.50 0.7934
    0.52 0.7934
    0.54 0.7934
    0.56 0.8033
    0.58 0.8098
    0.60 0.8230
  }
```

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
</tr>
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<tbody>
<tr>
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<td>0.9213</td>
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<tr>
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<tr>
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<td>0.9246</td>
</tr>
<tr>
<td>0.90</td>
<td>0.9246</td>
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<tr>
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<tr>
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</tr>
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<td>1.02</td>
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</tr>
<tr>
<td>1.04</td>
<td>0.4822</td>
</tr>
<tr>
<td>1.06</td>
<td>0.3115</td>
</tr>
<tr>
<td>1.08</td>
<td>0.1803</td>
</tr>
</tbody>
</table>
Appendix E

Sensor Model Matlab Code

% Tony Risvold
% Post-FINDO sensor model
% input is in W/cm^2
% output is image in digital counts
% close all;
clear all;

fname = 'C:\Documents and Settings\Administrator\My Documents\MATLAB\night.tif';

darkElectrons = .016^2/12^2/(15^2); % electrons/sec/pix
darkCurrent = 9e-13; % A/cm^2
readNoise = 8; % electrons
MtiTime = 0.1; % milliseconds
pixelSize = 24; % microns
overSample = 1;
waveLength = .7; % micron
focalLength = .420; % meters
tranOptics = 1.5;
tranFilter = 1;
obsuse = 0;
QIE = 1; % rel/cm

q = 6.6415e19; % e/colomb
b = 6.626e-34; % kg m^2/s
D = 2.597e8; % m/s

tNumber = 2;

imageIn = imread(fname, 'tif');
[N,M] = size(imageIn);
cutoff = 1/(wavelength^*wNumber); % meters
spatialPlan = |wavelength|^*wNumber; % meters
dist = zeros(11,11); % generate the FFT mesh
for m = -5:5
    for n = -5:5
        dist(m+5,n+5) = pi*sqrt(m^2+n^2)/|wavelength|^*wNumber/(pixelSize); % calculate the radius at each point in the raster image
    end
end
J = kernel1(dist); % generate kernel function
sone = 2J(1,:); % generate sone vector
sone(4,4)=1; % by definition sone(0,0)=1
sone = sone^*2; % find square
psf = sone.^2./sum(sum(sone)); % scaled so total power passed by the filter is 1
phoens = (image1^|wavelength|^*6)/(h*e); % pho/(a*cm^*2)
irrad = |phoens|transient*|pi|*(1-obscure))/1*(|wNumber|^2)]; % pho/(a*cm^2)
MTPapplied = infilter(irrad, psf, 'conv'); % pho/(a*cm^2)
signal = MTPapplied*|intTime|^*3*(pixelSize^*6)*2; %electrons
sampled = zeros(N/oversample,M/oversample); % sample the image
for n=1:N/oversample
    for m=1:M/oversample
        sampled(n,m) = sampled(n,m) + signal((n-1)*oversample+1,(m-1)*oversample)+1;
    end
end
darkoffset = darkCurrent*|intTime|^*3*(pixelSize^*6)*2*2; %electrons
noise = sqrt(darkoffset+sampled*readNoise^2*(GMP/|sqrt(12)|)^3); %REs electrons
avgNoise = mean(mean(noise));
avgSignal = mean(mean(sampled));
justNoise = (randn(N/oversample,M/oversample).*noise); % generate noise on the signal
toNoise = darkoffset+sampled+justNoise; % add the noise and dark current offset to the image
counts = int16(toNoise/QEE); % convert from electrons to digital counts
output = zeros(N, M);
outputNoise = zeros(N, M);
outputSignal = zeros(N, M);
[noise,noise] = size(counts);
for n=1:N % convert back to a full-size image
    for m=1:M
        thisN = ceill(n/oversample); %
        if thisN>noise
            thisM=noise;
        end
        thisN = ceill(m/oversample);
    end
end
if thisNoise
    thisNoise;
end

output(n,m) = counts(thisN, thinN);
outputNoise(n,m) = noise(thisN, thinN);
outputSignal(n,m) = signalN(thisN, thinN);
end

NoisePlate = outputNoise(105,120); % find the noise for the 15% reflector
NoiseCube = outputNoise(80,63); % find the noise for the 7% reflector

SignalPlate = outputSignal(105,120); % find the signal for the 15% reflector
SignalCube = outputSignal(80,63); % find the signal for the 7% reflector

G1QSNR = (SignalPlate-SignalCube)/avgNoise; \ determine the SNR according to the G1Q

sac = avgSignal/avgNoise; % find the average SNR for the image
figure, imagesc(counts, []);
figure, imagesc(output, []);
Appendix F

Sample SAMM2 Input File

C0 STANDARD INPUT FILE SAMM2. inp
C0 THIS FILE HOLDS THE DEFAULT VALUES FOR SAMM2
C0 THIS FILE IS UPDATED TO THE CURRENT VALUES OF THE PARAMETERS
C0 EACH TIME SAMM2 IS RUN.
C0 LINES WHICH HAVE A "C" IN COLUMN 1 ARE TREATED AS COMMENT
C0
C1 THE FIRST LINE CONTAINS THE INTERACTIVE/BATCH OPTION
C1 IF IT EQUALS 1, SAMM2 WILL RUN INTERACTIVELY, ALLOWING
C1 THE USER TO UPDATE OPTIONS. IF IT EQUALS 0, SAMM2 WILL
C1 RUN IN BATCH MODE.
C1
1
C2
C2 TITLE FOR CALCULATION
C2
C2 TEST CASE 1 - NO AND NO - TWO REGIONS [AURORAL]
C3 0. OUTPUT CONTROL PARAMETERS:
C3 1. MODEL ATMOSPHERE OUTPUT ==1 FOR FULL LISTING
C3 2. SELECTED TRANSITIONS ==1 FOR TRANSITIONS SELECTED
C3 3. MOLECULAR BAND INFORMATION ==1 FOR BAND INFORMATION
C3 4. NOT CURRENTLY USED
C3 5. HENRIETTA OUTPUT ==1 HENRIETTA ONLY ==2 FOR POST POPULATIONS
C3 6. AURORAL OUTPUT ==1 FINAL ONLY ==2 TIME DEVELOPMENT
C3 7. FINAL STATE POPULATIONS ==1 YES
C3 8. FINAL VIBRATIONAL TEMPERATURES ==1 YES
C3 9. LOG OUTPUT ==1 FOR COLUMN DENSITIES
C3 10. SPECTRAL RADIANCE OUTPUT ==1 FOR RADIANCE OUTPUT
C3 11. RADIANCE STATISTICS OUTPUT ==1 TO 3
C3 12. RADIANCE SPECTRAL INDEX ==1 FOR FIT TO COVARIANCE
C3 13. FILES FOR 2D/3D SCENE GENERATION == 1 FOR FILES
C3 1 2 3 4 5 6 7 8 9 10 11 12 13
0 1 1 0 1 1 1 1 0 0 0 0
C4 FILE NAME FOR SAMM2 SPECTRAL RADIANCE OUTPUT FILE
C4
C5 FILE NAME FOR SAMM2 TRANSMISSION OUTPUT FILE
C5
C6 FILE NAME FOR SAMM2 GENERAL OUTPUT FILE NAME
C6
APPENDIX F. SAMPLE SAMM2 INPUT FILE

CK
TEST1.OUT
C7 CASE SELECTION FOR OUTPUT FILES
C7 APPLIES ONLY TO LOCAL FILE NAME NOT THE PATH
C7 UPPPER
C8 DIRECTORY PATH FOR OUTPUT FILES
C9
OUTdir/
C0000000 END OF INNAME OUTPUT FILE NAME INPUT
C2
C2000000 START OF INSTD STANDARD SETUP INPUT
C0-26 INSTDM
C9
C9 DIRECTORY PATH FOR KINETICS FILES LINK/STATS/BANDS
C0
Kinfdir/
C10 PREFIX FOR DEFAULT ROTATION AMBIENT LINKING FILES
C10 CAN BE BLANK IF MOLECULAR FORMULA STARTS THE FILE NAME
C10 .CKL
C11 SUFFIX FOR DEFAULT ROTATION AMBIENT LINKING FILES
C11 CAN BE BLANK IF MOLECULAR FORMULA ENDS THE FILE NAME
C11 .CKL
C12 PREFIX FOR DEFAULT ROTATION AURORAL LINKING FILES
C12 CAN BE BLANK IF MOLECULAR FORMULA STARTS THE FILE NAME
C12 .A
C13 SUFFIX FOR DEFAULT ROTATION AURORAL LINKING FILES
C13 CAN BE BLANK IF MOLECULAR FORMULA ENDS THE FILE NAME
C13 .A
C14 PREFIX FOR DEFAULT ROTATION AMBIENT STATES FILES
C14 CAN BE BLANK IF MOLECULAR FORMULA STARTS THE FILE NAME
C14 .STA
C15 SUFFIX FOR DEFAULT ROTATION AMBIENT STATES FILES
C15 CAN BE BLANK IF MOLECULAR FORMULA ENDS THE FILE NAME
C15 .STA
C16 PREFIX FOR DEFAULT ROTATION AURORAL STATES FILES
C16 CAN BE BLANK IF MOLECULAR FORMULA STARTS THE FILE NAME
C16 .A
C17 SUFFIX FOR DEFAULT ROTATION AURORAL STATES FILES
C17 CAN BE BLANK IF MOLECULAR FORMULA ENDS THE FILE NAME
C17 .A
C18 PREFIX FOR DEFAULT ROTATION AMBIENT BANDS FILES
C18 CAN BE BLANK IF MOLECULAR FORMULA STARTS THE FILE NAME
C18 .BND
C19 SUFFIX FOR DEFAULT ROTATION AMBIENT BANDS FILES
C19 CAN BE BLANK IF MOLECULAR FORMULA ENDS THE FILE NAME
C19 .BND
C20 CASE SELECTION FOR KINETICS FILES
C20 APPLIES ONLY TO LOCAL FILE NAME NOT THE PATH
C20 UPPPER
C21 DIRECTORY PATH FOR ATMOSPHERIC PROFILES
C21 atmoph/
C22 CASE SELECTION FOR ATMOSPHERIC PROFILES
C22 APPLIES ONLY TO LOCAL FILE NAME NOT THE PATH
C22 UPPPER
C23 DIRECTORY PATH FOR EXCITED STATES POPULATION FILES
C23 popdir/
C24 CASE SELECTION FOR STANDARD POPULATION FILES
C24 APPLIES ONLY TO LOCAL FILE NAME NOT THE PATH
C24 UPPPER
C25 SUPPRESSION/NONSUPPRESSION OF RUN TIME WARNING MESSAGES
SUPPRESSION
C26 DIRECTORY PATH FOR SAMM2 LINE FILE
APPENDIX F. SAMPLE SAMM2 INPUT FILE

C*6 NUMBER OF RADIATORS IN ENVIRONMENT ONE
C*6
1
C*1 MOLECULAR FORMULA FOR SPECIES
C*2
HO
1 0.100E+01
C*2 SPECIES LINKING FILE
C*2
HO.CEL
C*3 SPECIES STATES FILE
C*3
HO.STA
C*4 SPECIES BANDS FILE
C*4
HO.BND
C#1 POPULATION FILE NAME AND SAVE INDEX FOR ENVIRONMENT TWO
C#2
ATEST1.POP 1
C#2 NUMBER OF RADIATORS IN ENVIRONMENT TWO
C#2
2
C*1 MOLECULAR FORMULA FOR SPECIES
C*2
HO
1 0.100E+01
C*2 SPECIES LINKING FILE
C*2
HO.CEL
C*3 SPECIES STATES FILE
C*3
HO.STA
C*4 SPECIES BANDS FILE
C*4
HO.BND
C#3 USER OR CODE DEFINED AURORAL INDEX
C#2
1
C#4 AURORAL IBC INDEX
C#4
1
C#5 DISTRIBUTION INDEX, TOTAL ENERGY, CHARACTERISTIC ENERGY,
C#5 AND SCALE PARAMETER
C#5
1 0.10000E+03 0.30000E+01 0.60000E+00
C#6 DOSE TIME AND OBSERVATION TIME (SEC)
C#6
0.10000E+03 0.10000E+03
C*7 ORIGIN OF REGION COORDINATE SYSTEM INDEX
C*7
0
C*8 FOUR LATITUDES FOR LOCAL REGION CORNERS (DEGREES)
C*8
0.10000E+02 0.30000E+02 0.30000E+02 0.30000E+02
C*9 FOUR LONGITUDES FOR LOCAL REGION CORNERS (DEGREES)
C*9
0.10000E+02 0.10000E+02 0.30000E+03 0.30000E+03
C*10 UPPER AND LOWER ALTITUDES OF LOCAL REGION (Km)
C*10
0.15000E+02 0.50000E+02
C#8 SUN OR MOON, SOLAR IRRADIANCE FILE NAME, SOLAR
C#8 IRRADIANCE SCALING FACTOR, DURATION OF NOON
C#8
0 MENERUR.DAT 0.00 180.00
C#8 BOUNDARY TEMPERATURE, GROUND ALTIMETRY, SURFACE REFLECTANCE
C#9 OPTIONS, ALBEDO, BROT OR LANDERION INPUT FILE NAME
C#9
0.00 0.00 0.00 0.00 0.00
C#9 MULTIPLE SCATTERING, DISORT ALGORITHMS, DISORT
C#9 ATTENUATION DEPENDENCE, NUMBER OF STREAMS
C#9
0 1 0
C#1 AEROSOL TYPE, SEASONAL AEROSOL PROFILE, STRATOSPHERIC
C#1 AEROSOL TYPE, AEROSOL AM. VBA, CLOUD/FOG HEIGHT AND THICKNESS,
157

C41 INVERSION LAYER HEIGHT
C42
0 0 1 0 0 0.00 0.00 0.00
C43 VISIBILITY, WIND SPEED, AVERAGE WIND SPEED, SCATTERING
C44 MUSE FUNCTION, ASYMMETRY PARAMETER
C45
0.00 0.00 0.00 2 -9.00
C46 CLOUD TYPE, RAIN RATE, CLOUD THICKNESS, BASE ALTITUDE,
C47 EXTINCTION COEFFICIENT, NUMBER OF BOUNDARIES AND WAVELENGTHS
C48
0 0.00 -9.00 -9.00 -9.00 -9 -9
C49 REFERENCE WAVELENGTH FOR EXTINCTION, WATER DROPLET AND ICE
C50 PARTICLE COLUMN DENSITY, RELATIVE HUMIDITY, WATER DROPLET
C51 AND ICE PARTICLE ASYMMETRY PARAMETERS
C52
-9.00 -9.00 -9.00 -9.00 -9.00 -9.00
C53 MINIMUM FREQUENCY, MAXIMUM FREQUENCY AND RESOLUTION (CM-1)
C54
0.150000E+04 0.400000E+04 0.100000E+01
C55 NUMBER OF SPECIES FOR RADIANCE CALCULATION
C56
2
C57 MOLECULAR FORMULA AND ISOTOPIC NUMBER
C57
NO 1
C57 MOLECULAR FORMULA AND ISOTOPIC NUMBER
C57
NO 1